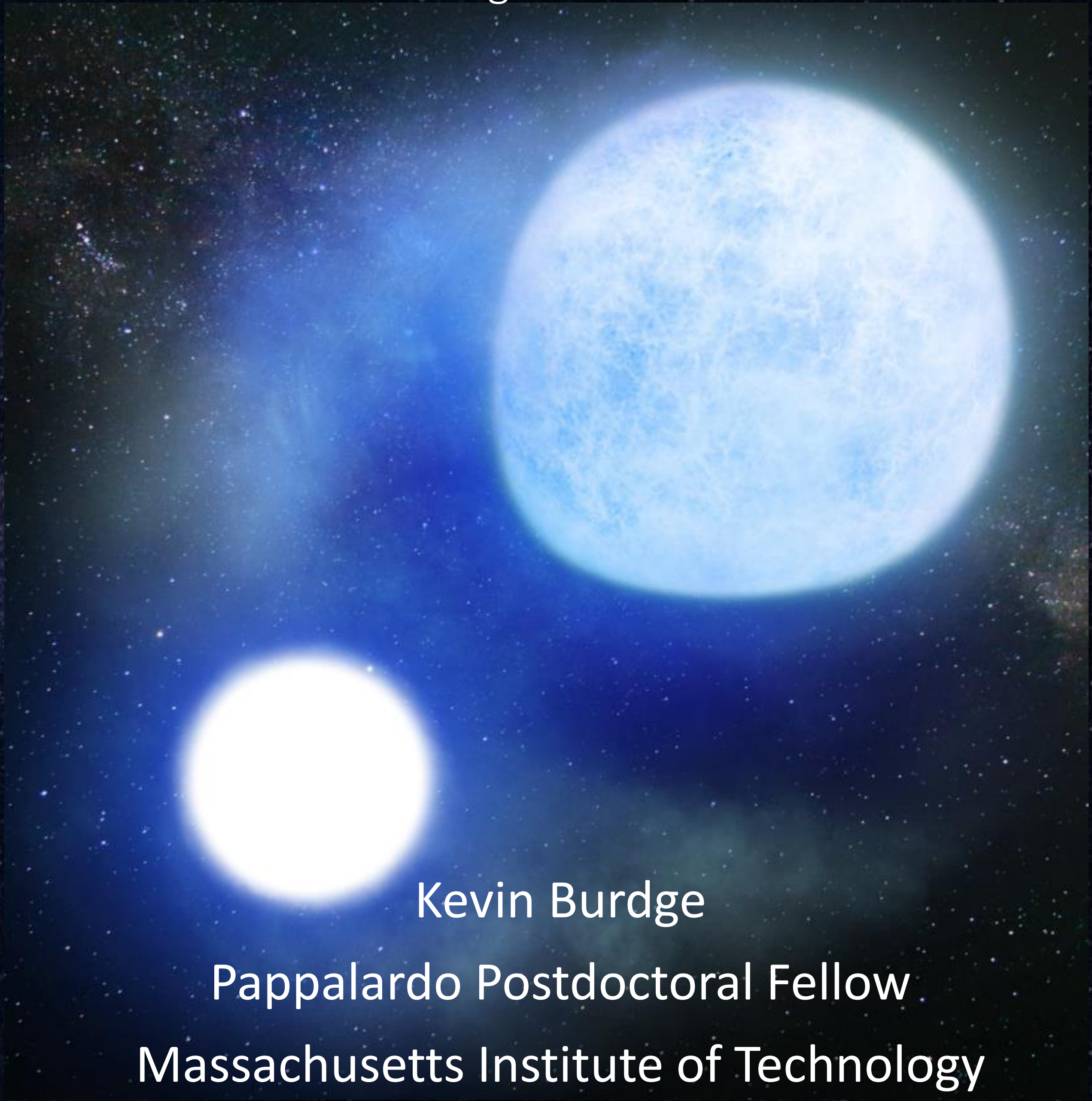
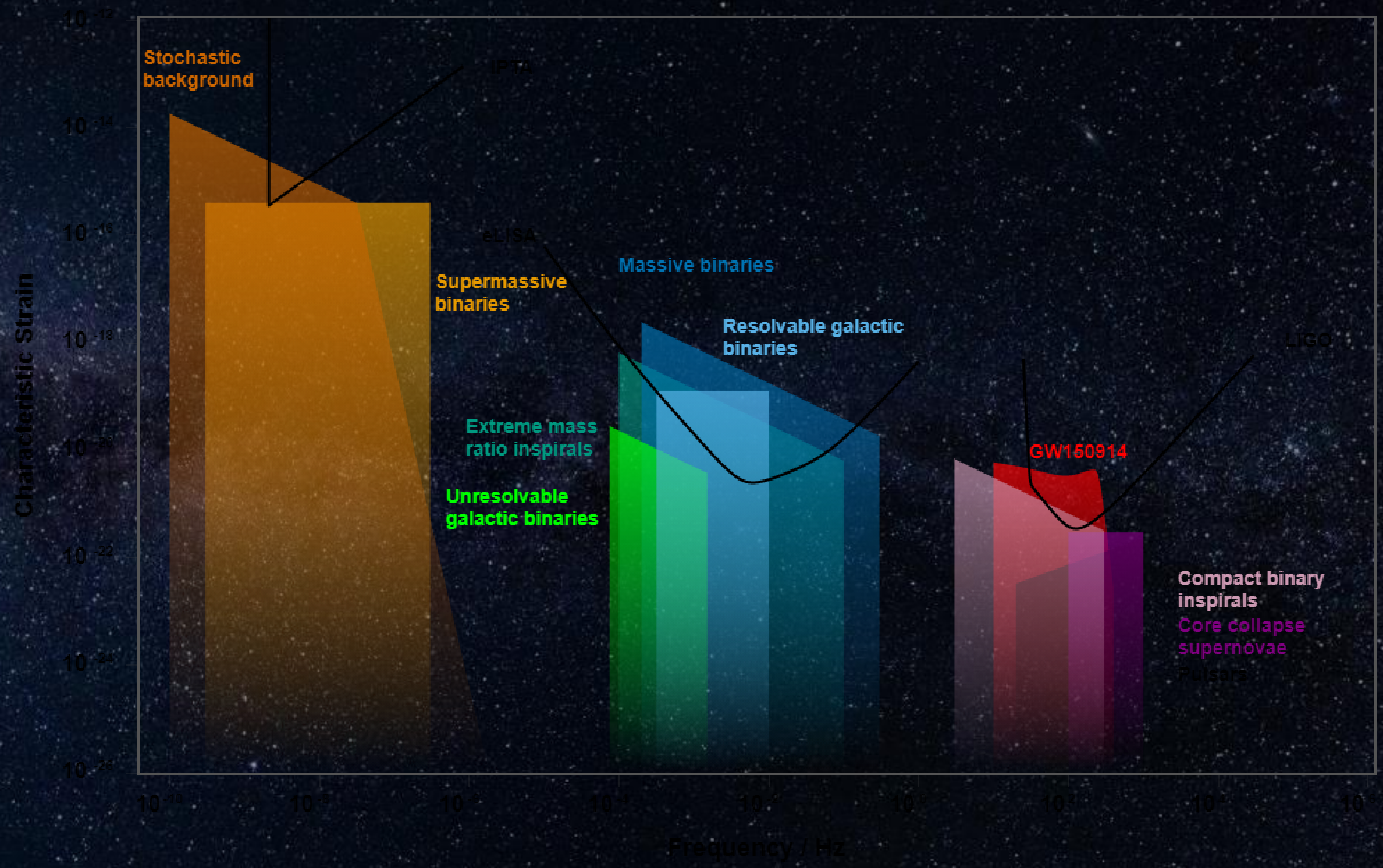
Progress and prospects in detecting sources of millihertz gravitational waves using electromagnetic radiation



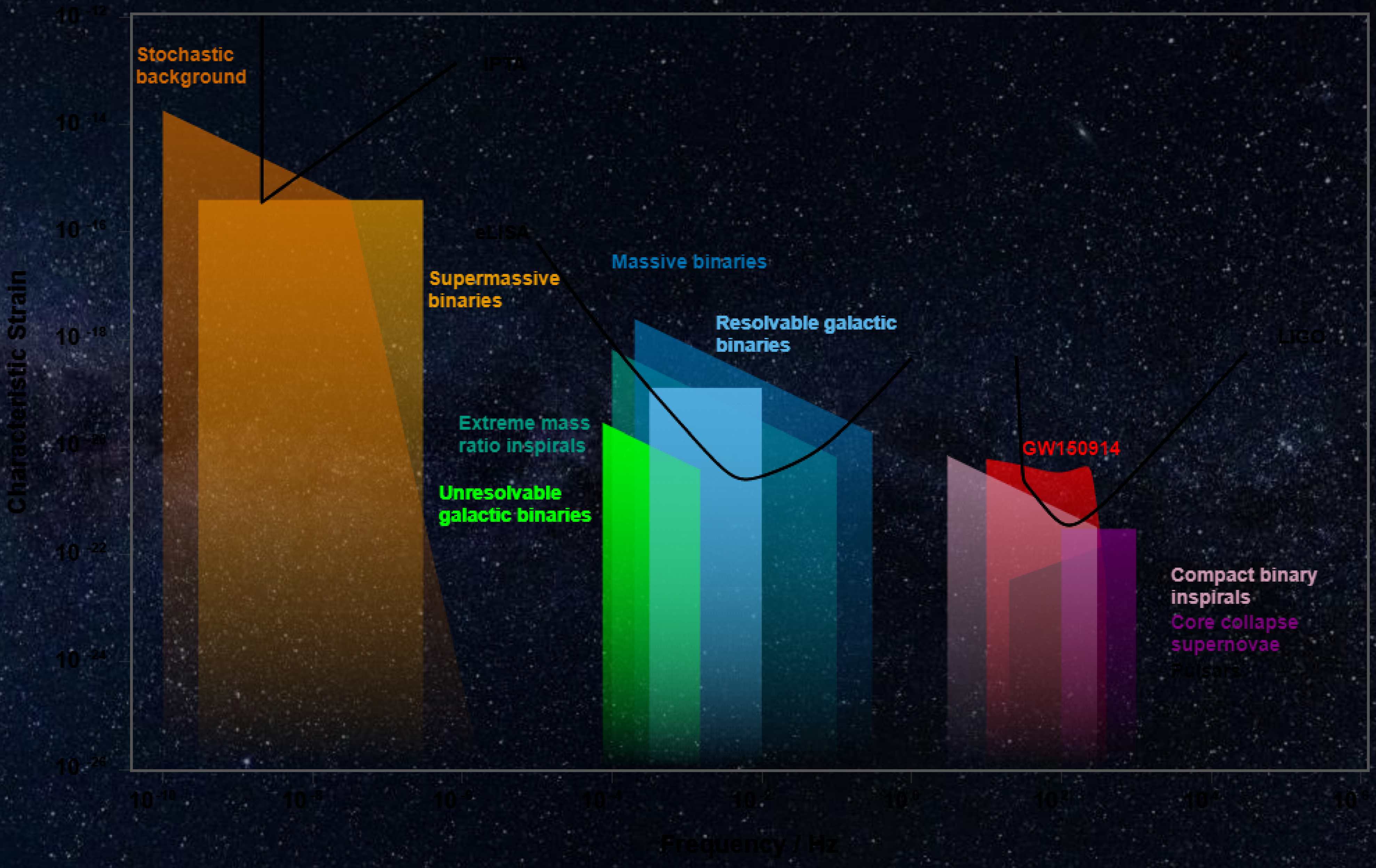
Kevin Burdge

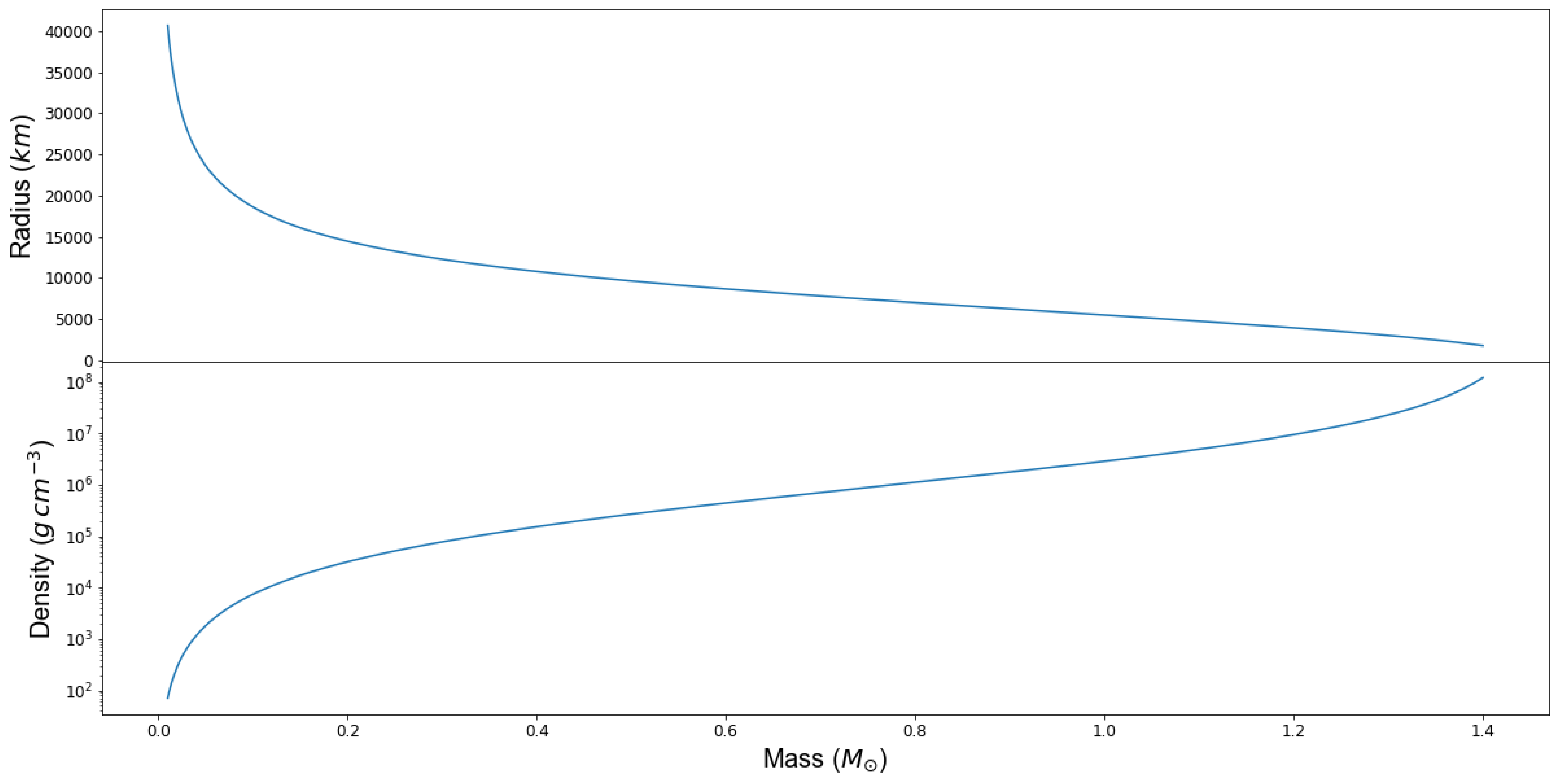
Pappalardo Postdoctoral Fellow

Massachusetts Institute of Technology

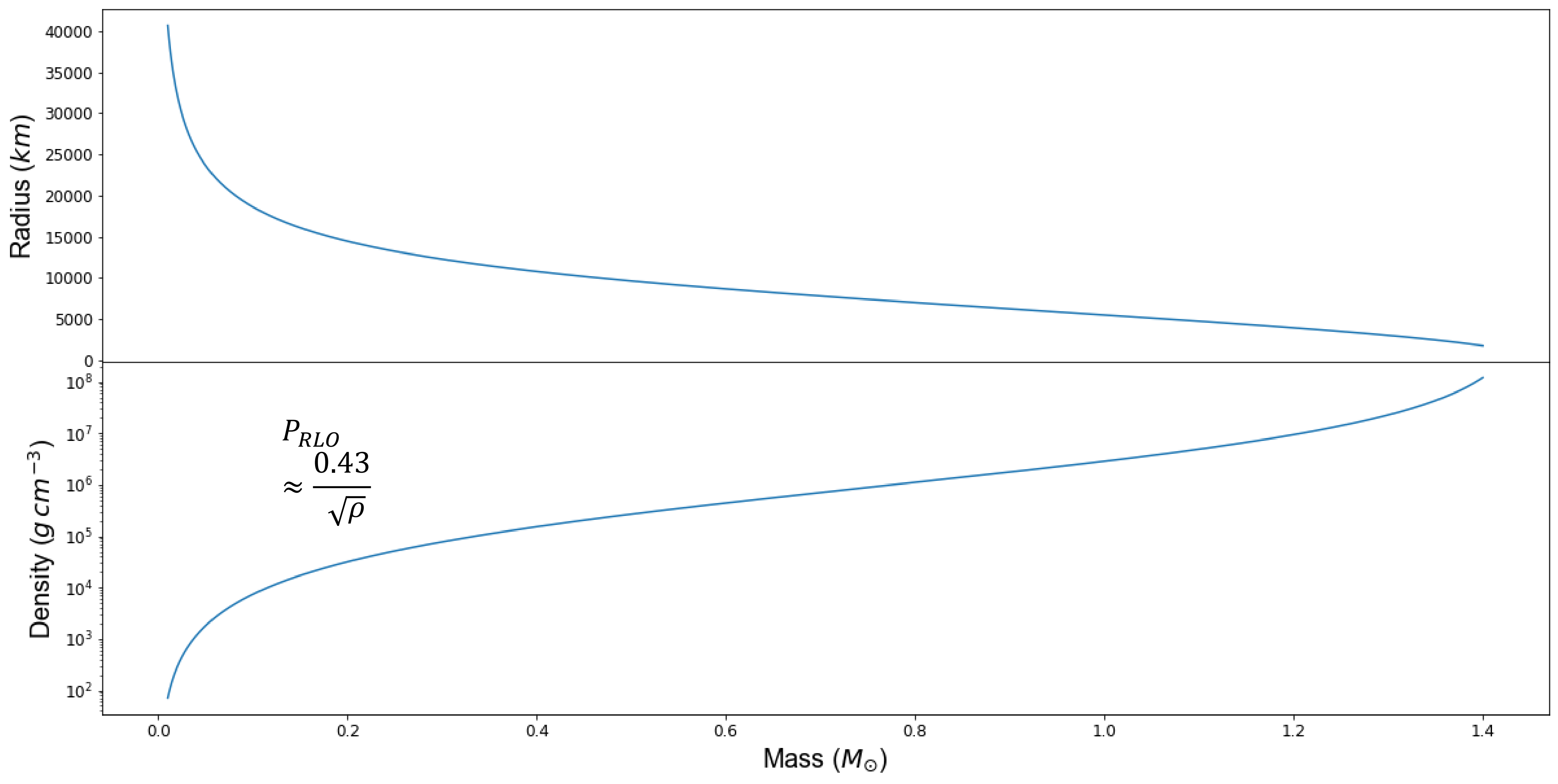


Stochastic background
Supermassive binaries
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
GW150914
Compact binary inspirals
Core collapse supernovae

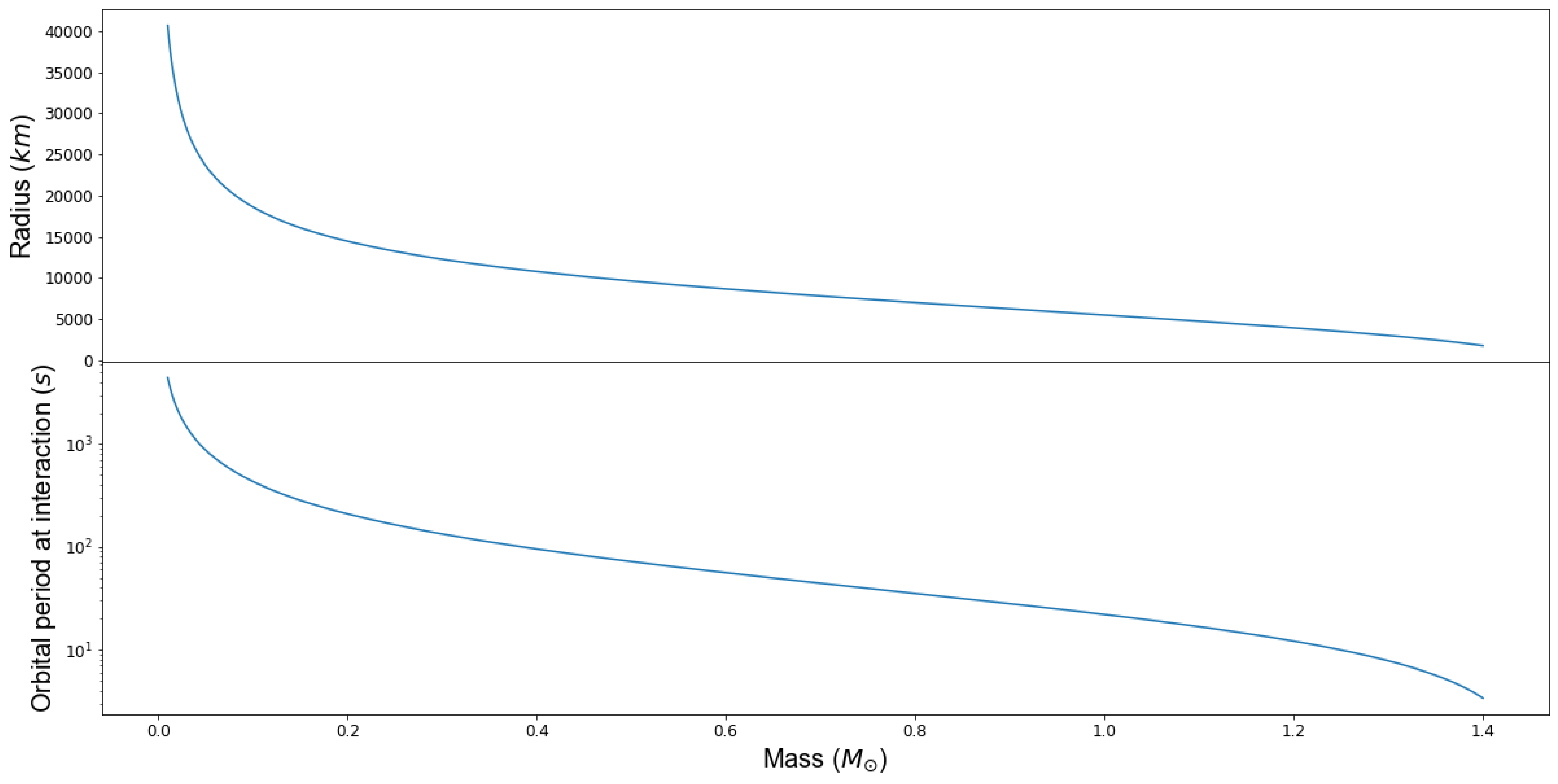

Stochastic background
Supermassive binaries
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
GW150914
Compact binary inspirals
Core collapse supernovae
Characteristic Strain



Radius (km)
40000
35000
30000
25000
20000
15000
10000
5000
0
Density ($g\,cm^{-3}$)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Mass ($M_\odot$)



$$P_{RLO} \approx \frac{0.43}{\sqrt{\rho}}$$



Radius (km)
40000
35000
30000
25000
20000
15000
10000
5000
0
Orbital period at interaction (s)
10^3
10^2
10^1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Mass ($M_\odot$)


48 inch Samuel Oschin
Schmidt telescope

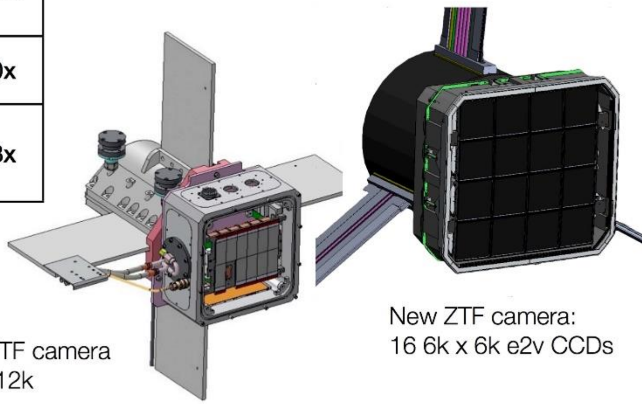
Discovery: using the Zwicky Transient Facility

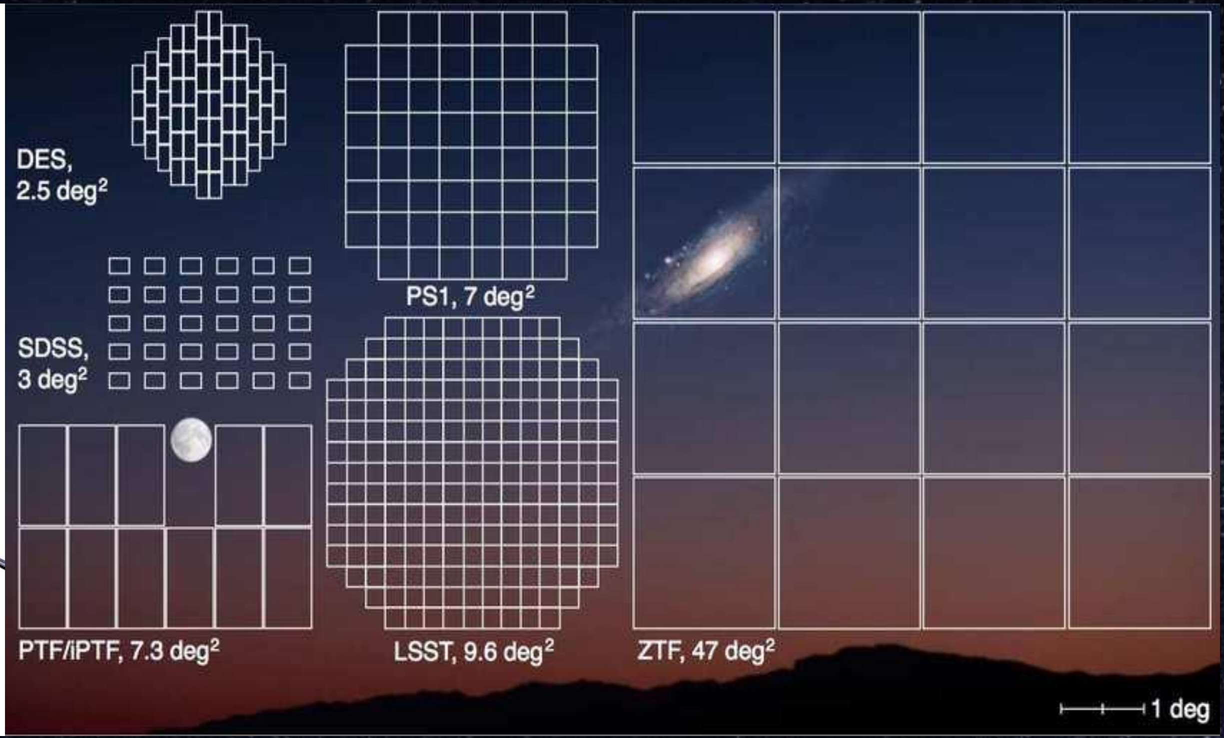
ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**15.0x**
Relative Volumetric Survey Rate	1x	**12.3x**

3750 deg^2/hour
⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey





The crucial element: ZTF has a large field of view, and accumulates many images quickly

But it’s not trivial to find these objects…

Searching for minute periods in data sampled over months to years->enormous frequency grids

Graphics processing units help a lot with this

But it’s not trivial to find these objects…

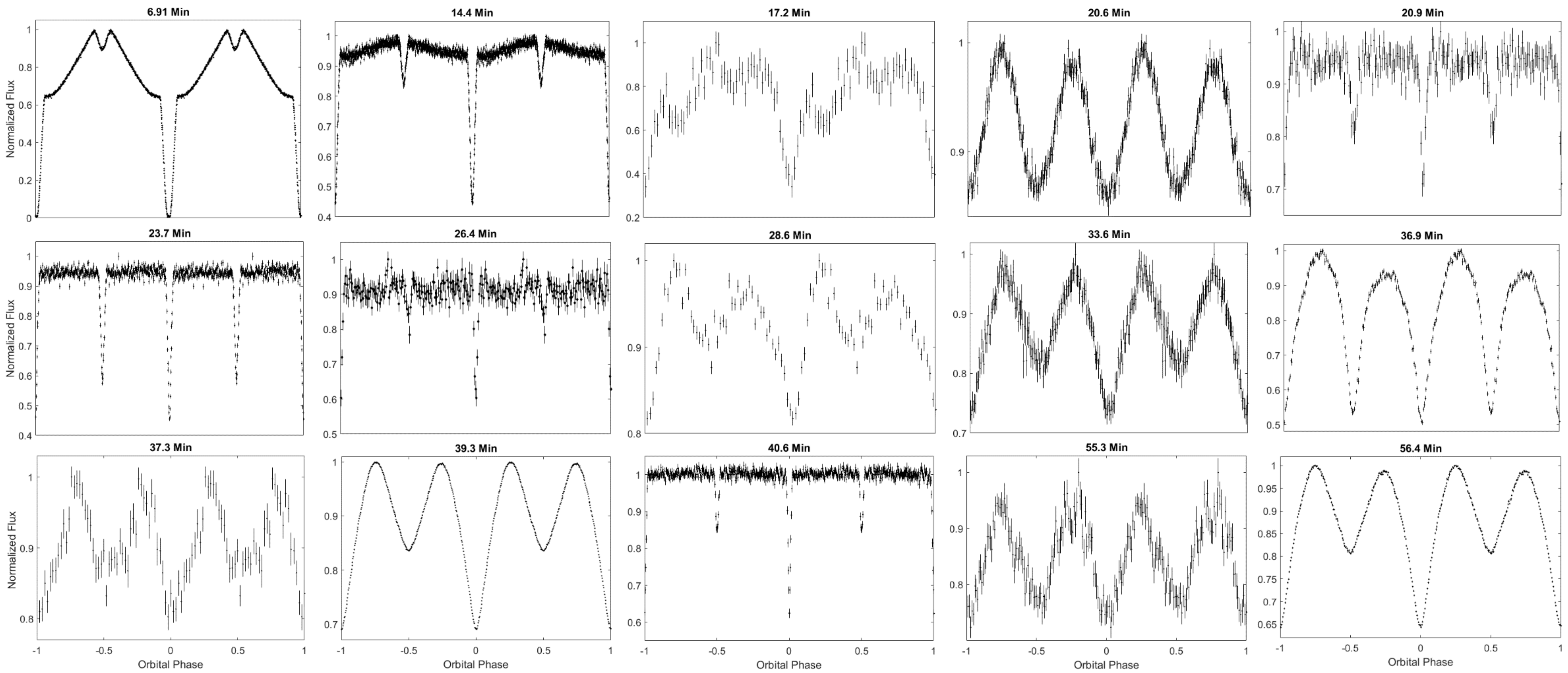
What's new with algorithms?

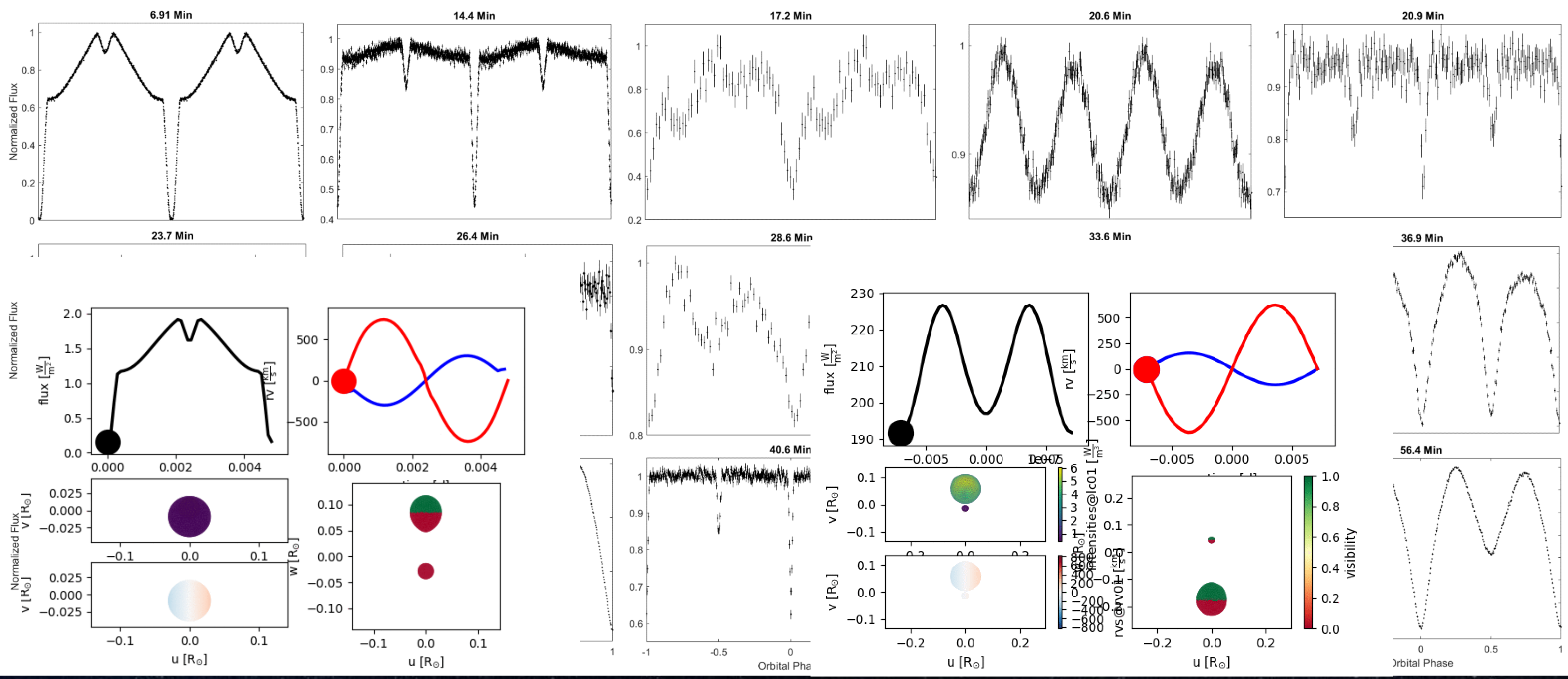
- Period finding on GPUs is orders of magnitude faster than on a CPU when implemented correctly.

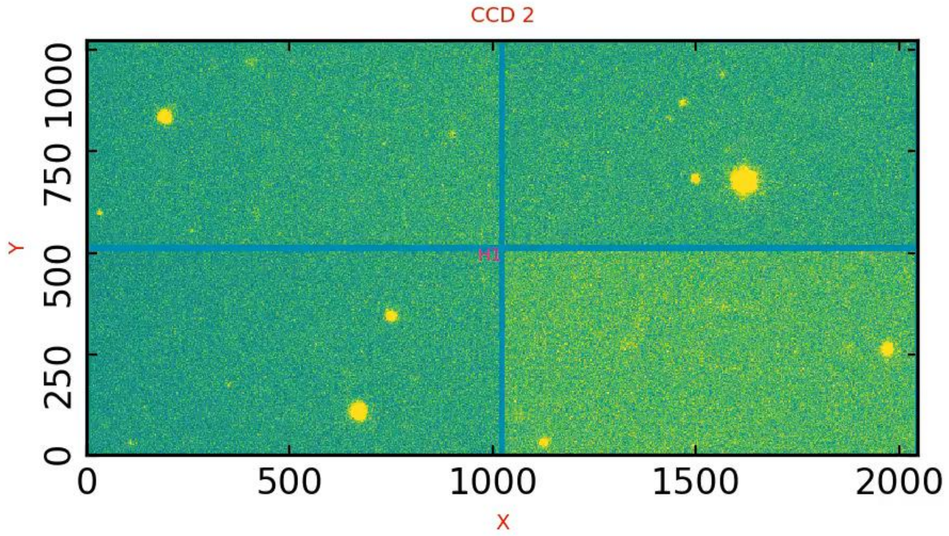
- I have successfully implemented a fast coherent acceleration search GPU based algorithm, optimized for large scale time domain surveys operating on a fixed field grid.

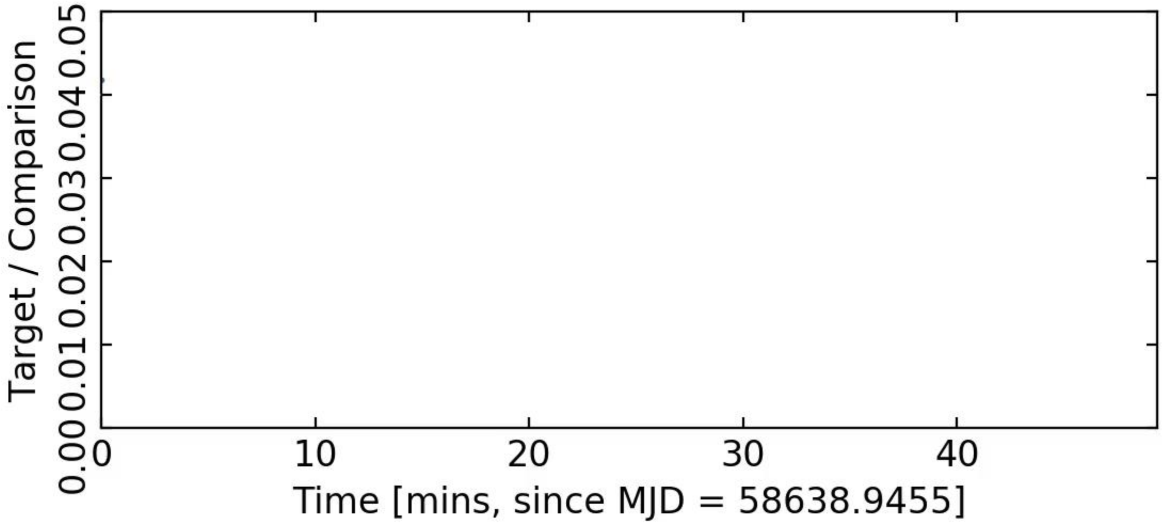
- I have now period searched 1.22 billion sources to frequencies of 720 cycles per day. There is a lot there…

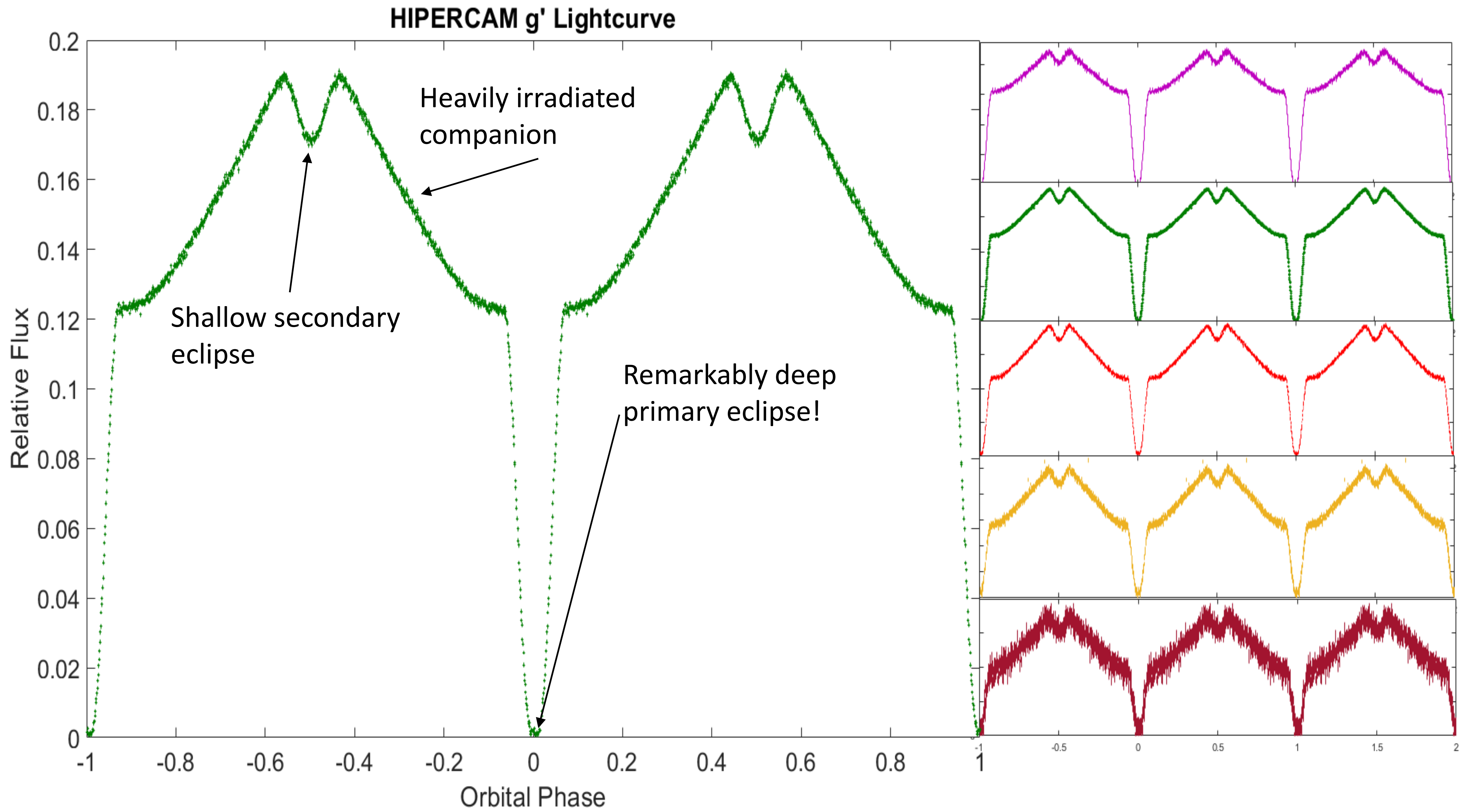
Okay, now let's get to the good stuff

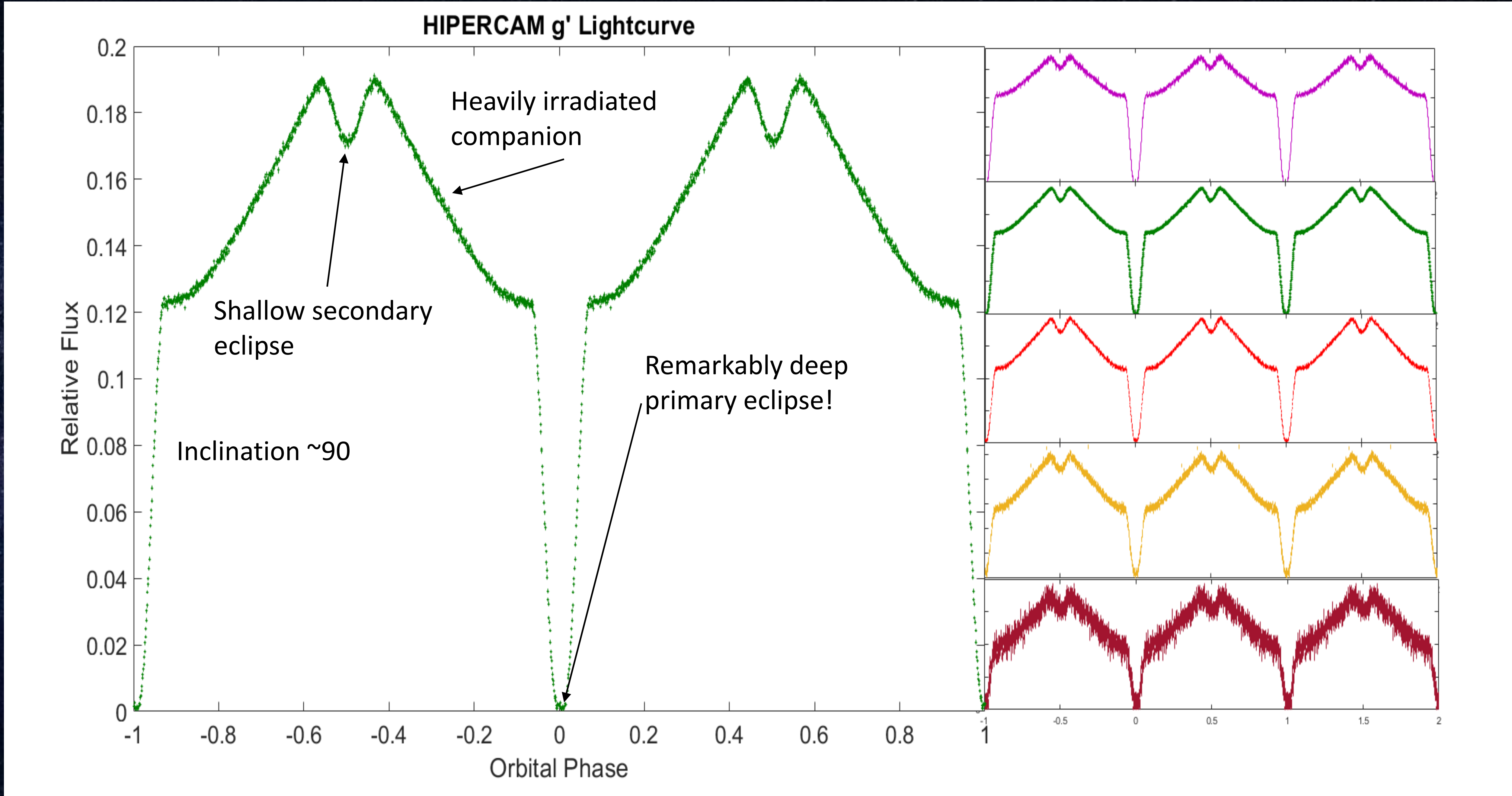

6.91 Min
14.4 Min
17.2 Min
20.6 Min
20.9 Min
23.7 Min
26.4 Min
28.6 Min
33.6 Min
36.9 Min
37.3 Min
39.3 Min
40.6 Min
55.3 Min
56.4 Min
Normalized Flux
Orbital Phase


6.91 Min
14.4 Min
17.2 Min
20.6 Min
20.9 Min
23.7 Min
26.4 Min
28.6 Min
33.6 Min
36.9 Min
40.6 Min
56.4 Min
Normalized Flux
Orbital Phase
flux [W/m²]
rv [km/s]
v [R☉]
w [R☉]
u [R☉]
intensities@lc01
rvs@rv01
visibility

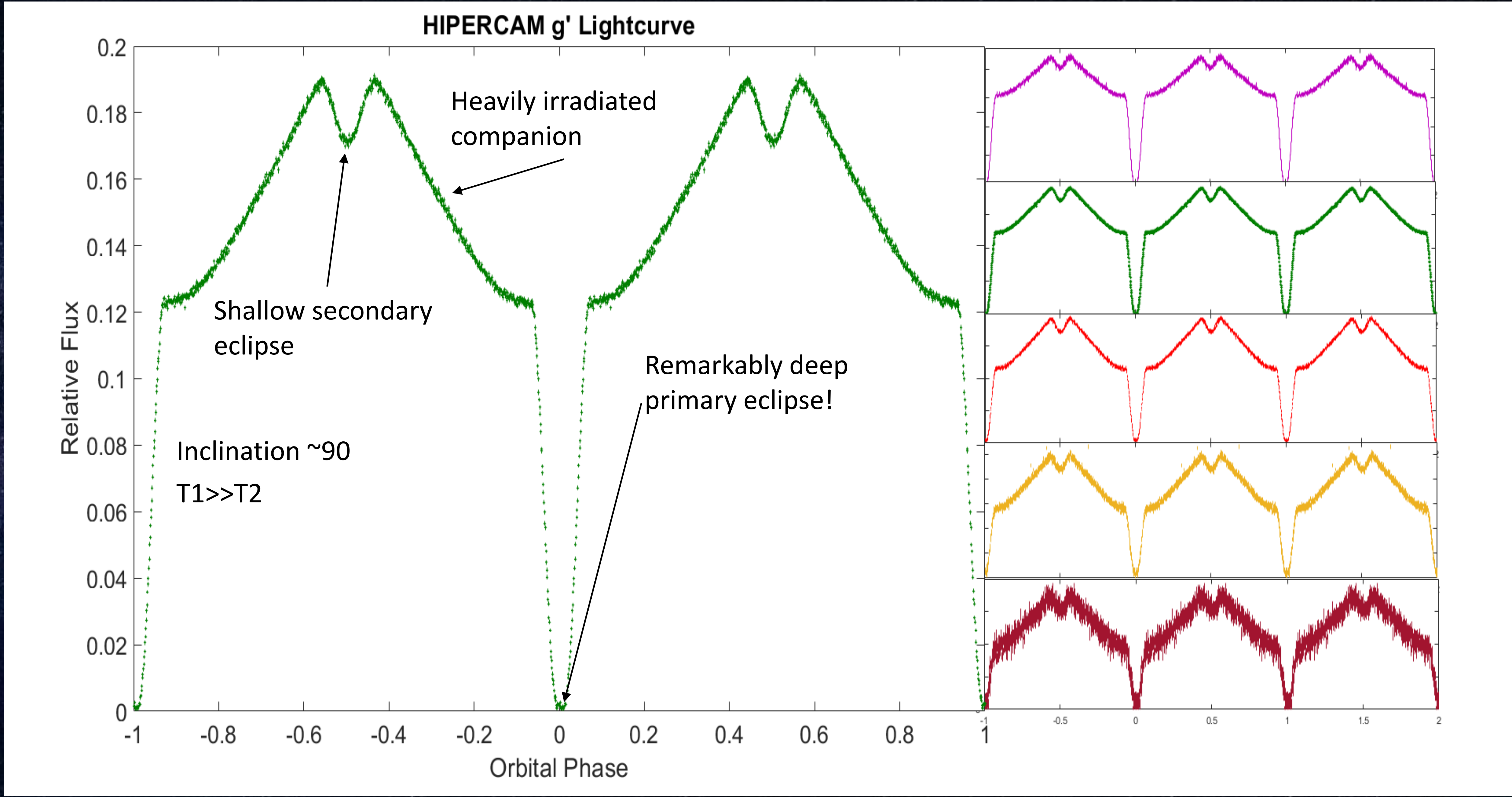

CCD 2
Y
X
H1
0
250
500
750
1000
0
500
1000
1500
2000

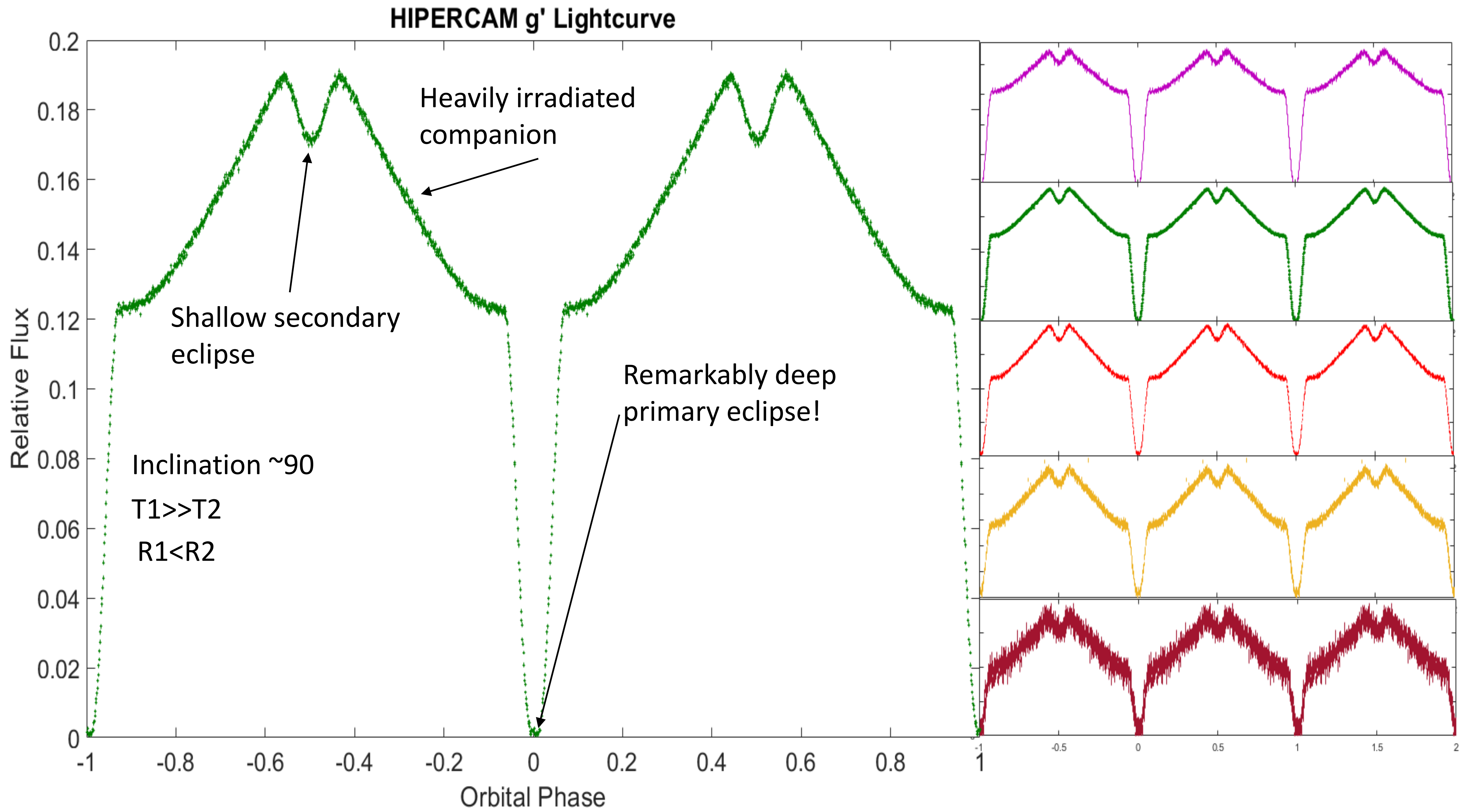

Target / Comparison
Time [mins, since MJD = 58638.9455]
0.00
0.01
0.02
0.03
0.04
0.05
0
10
20
30
40


HIPERCAM g' Lightcurve
Relative Flux
Orbital Phase
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
-1
-0.5
0
0.5
1
1.5
2

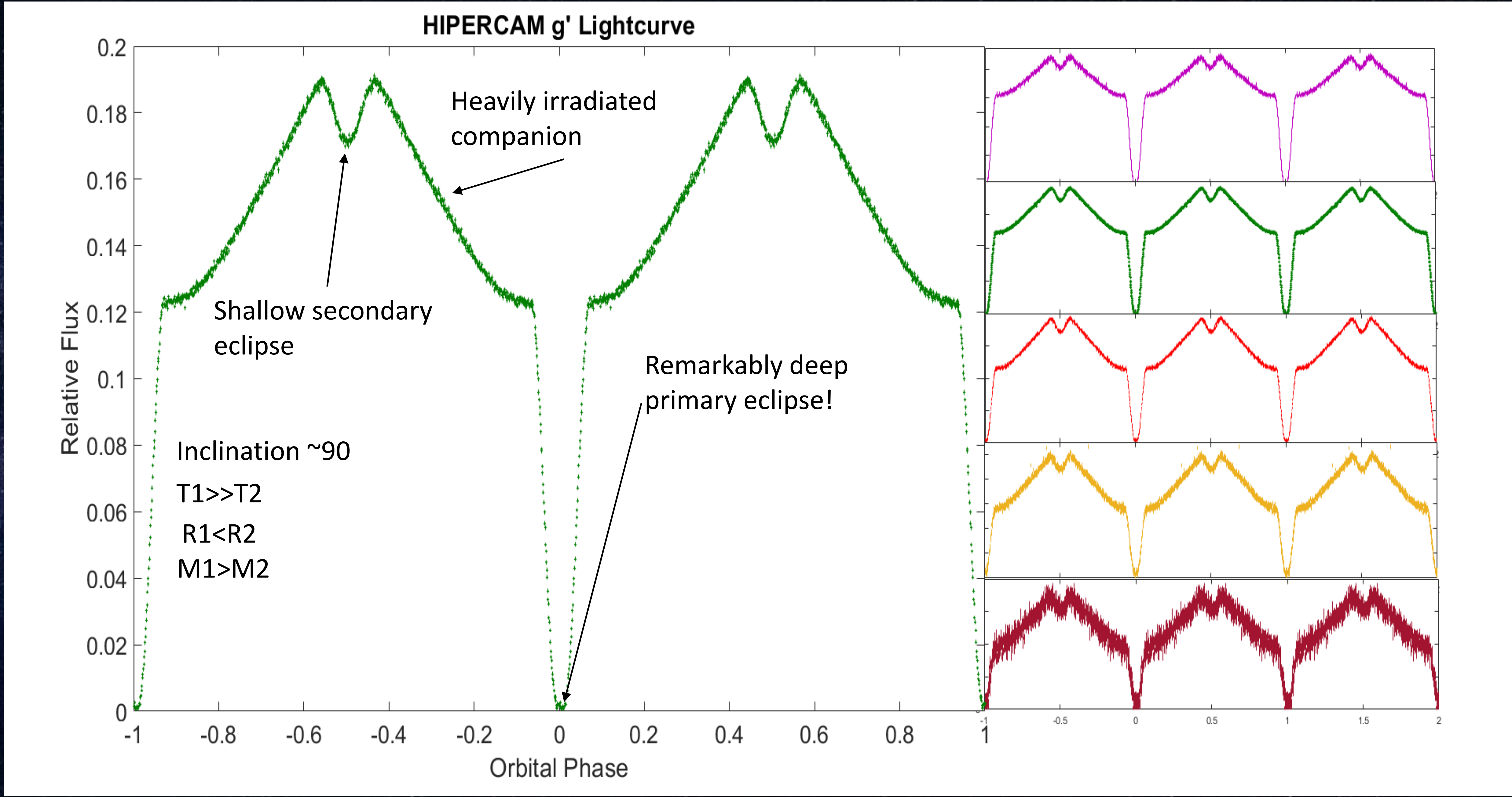


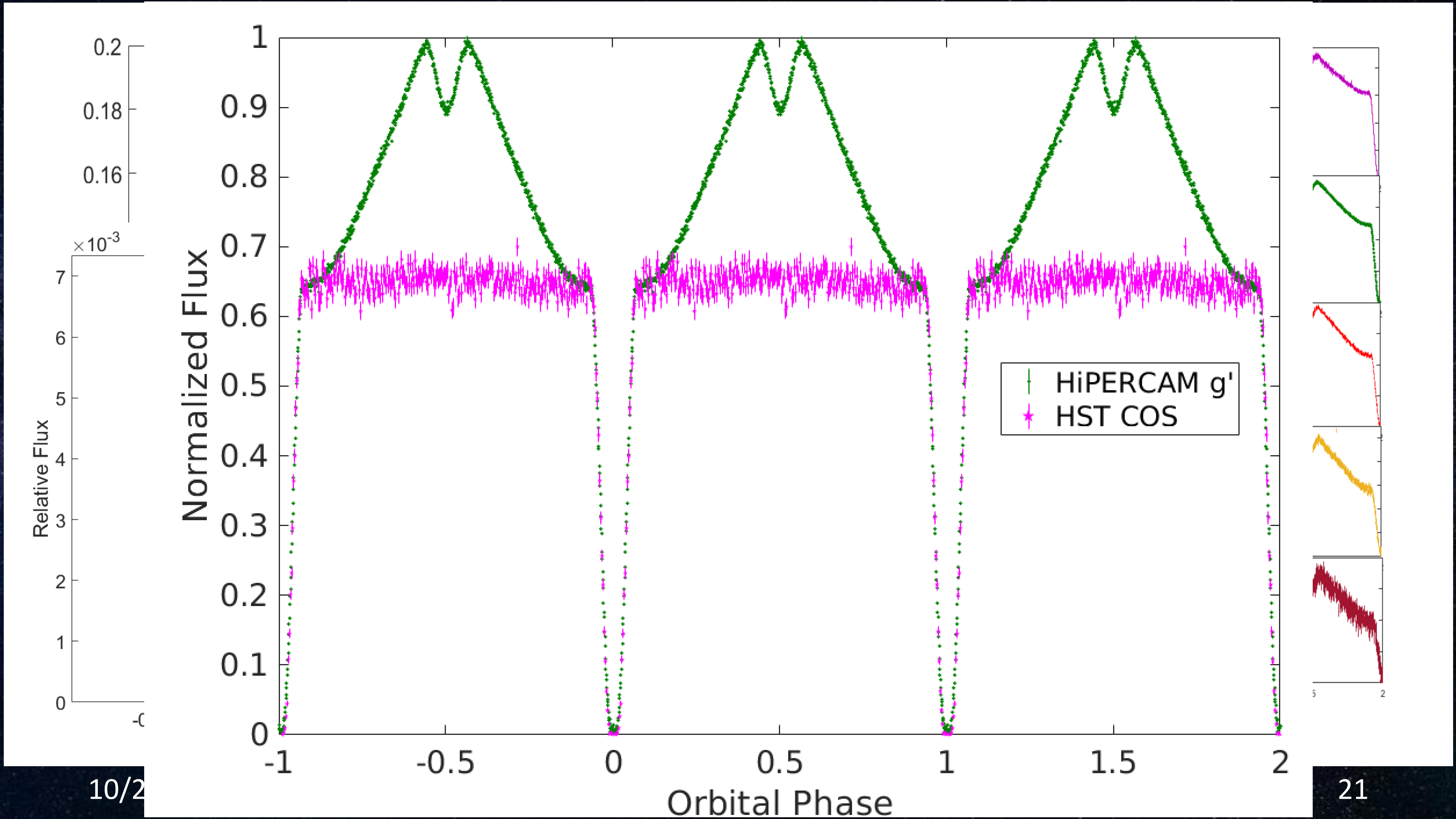
HIPERCAM g' Lightcurve
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
Inclination ~90
Relative Flux
Orbital Phase
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
-0.5
0
0.5
1
1.5
2


HIPERCAM g' Lightcurve
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
Inclination ~90
T1>>T2
Relative Flux
Orbital Phase

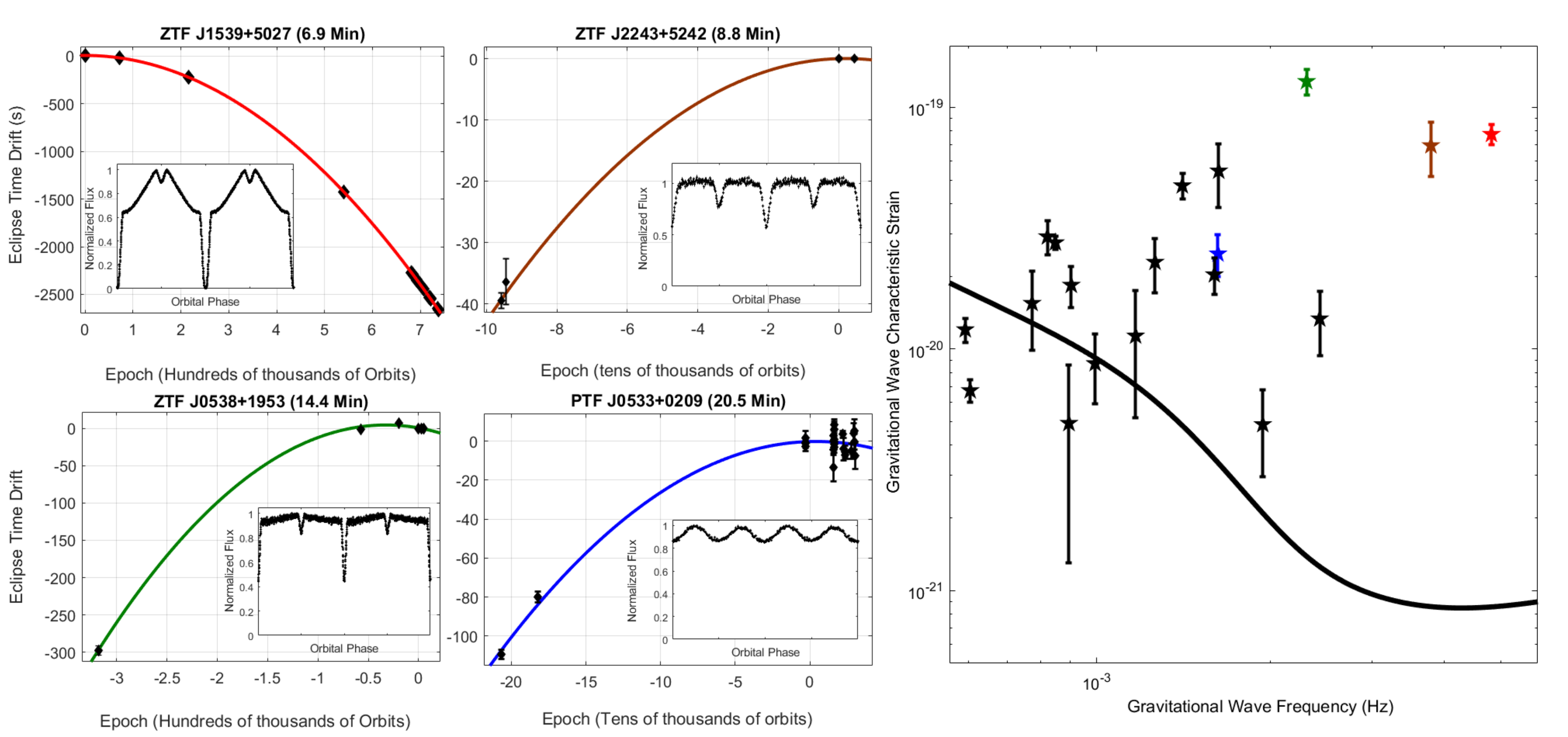


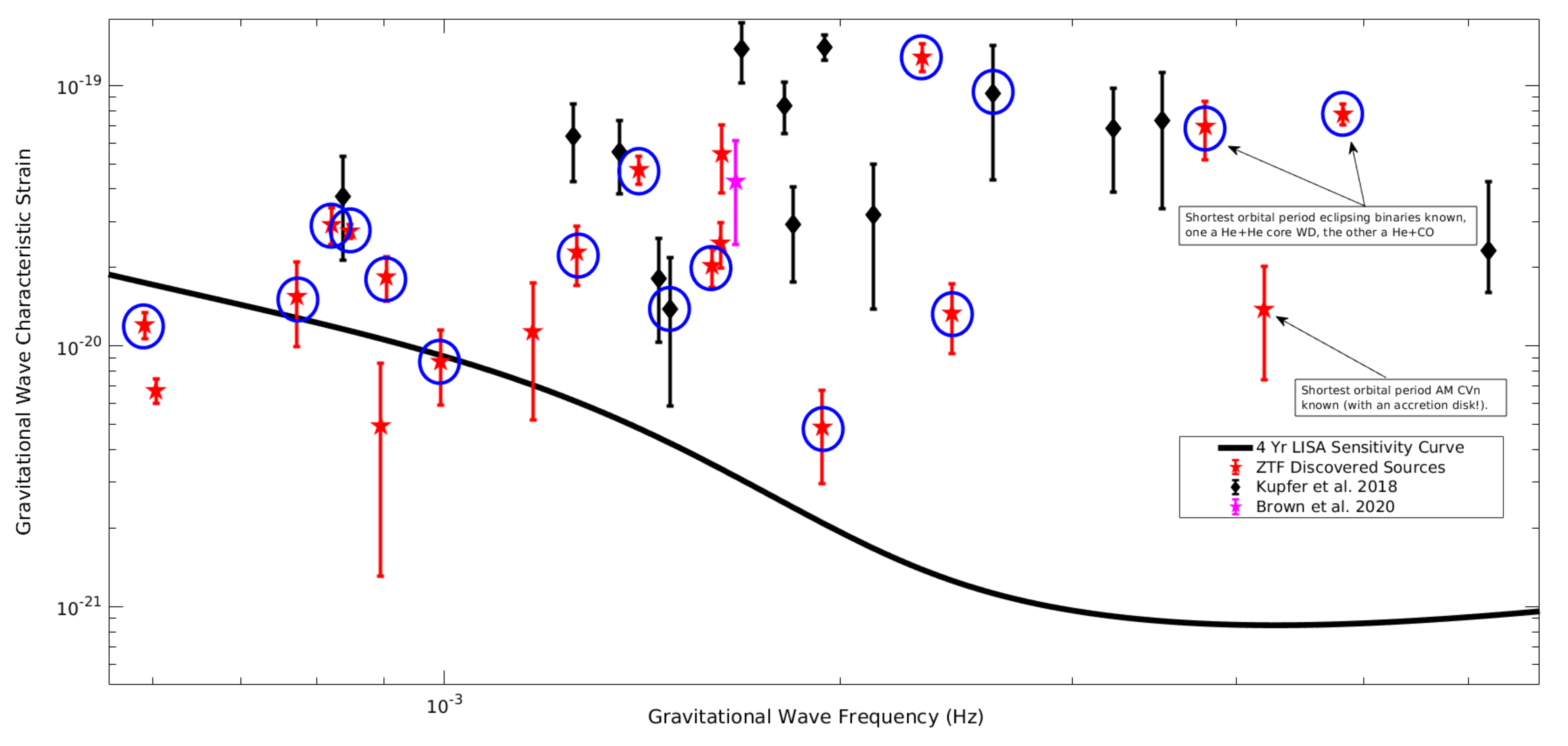
HIPERCAM g' Lightcurve
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
Inclination ~90
T1>>T2
R1<R2
Relative Flux
Orbital Phase
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
-0.5
0
0.5
1
1.5
2


HIPERCAM g' Lightcurve
Heavily irradiated companion
Shallow secondary eclipse
Remarkably deep primary eclipse!
Inclination ~90
T1>>T2
R1<R2
M1>M2
Relative Flux
Orbital Phase
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
-0.5
0.5
1.5
2



Normalized Flux
Orbital Phase
HiPERCAM g'
HST COS
Relative Flux


ZTF J1539+5027 (6.9 Min)
ZTF J2243+5242 (8.8 Min)
ZTF J0538+1953 (14.4 Min)
PTF J0533+0209 (20.5 Min)
Eclipse Time Drift (s)
Eclipse Time Drift
Normalized Flux
Orbital Phase
Epoch (Hundreds of thousands of Orbits)
Epoch (tens of thousands of orbits)
Epoch (Tens of thousands of orbits)
Gravitational Wave Characteristic Strain
Gravitational Wave Frequency (Hz)



Gravitational Wave Characteristic Strain
Gravitational Wave Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-3}
Shortest orbital period eclipsing binaries known, one a He+He core WD, the other a He+CO
Shortest orbital period AM CVn known (with an accretion disk!).
4 Yr LISA Sensitivity Curve
ZTF Discovered Sources
Kupfer et al. 2018
Brown et al. 2020

What are we learning from these systems?

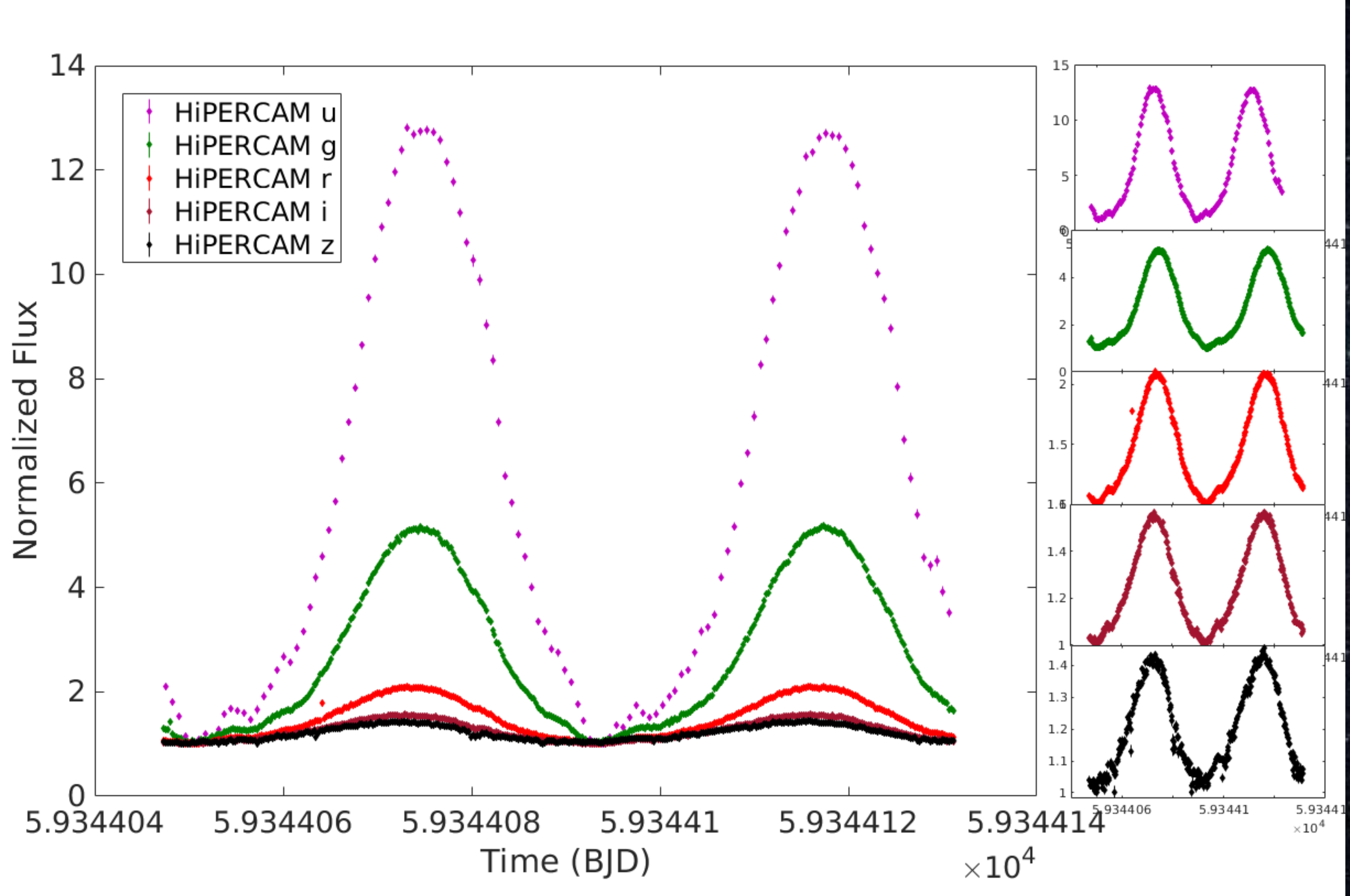
- Binary evolution channels (e.g. we see merging pairs of He Core WDs, CO+He core, and AM CVns undergoing stable mass-transfer)
- Tides in white dwarfs. We can measure these in several ways (spectroscopically, and also via orbital evolution).
- We are getting precise parameter estimates of the WD EOS, and can study deviations from it introduced by effects such as mass-transfer.
- The above are all things we can do with photons from the ground-- even more tests of physics in these systems will come along with the launch of LISA.

Some sneak peaks of new results:

- First, something already published

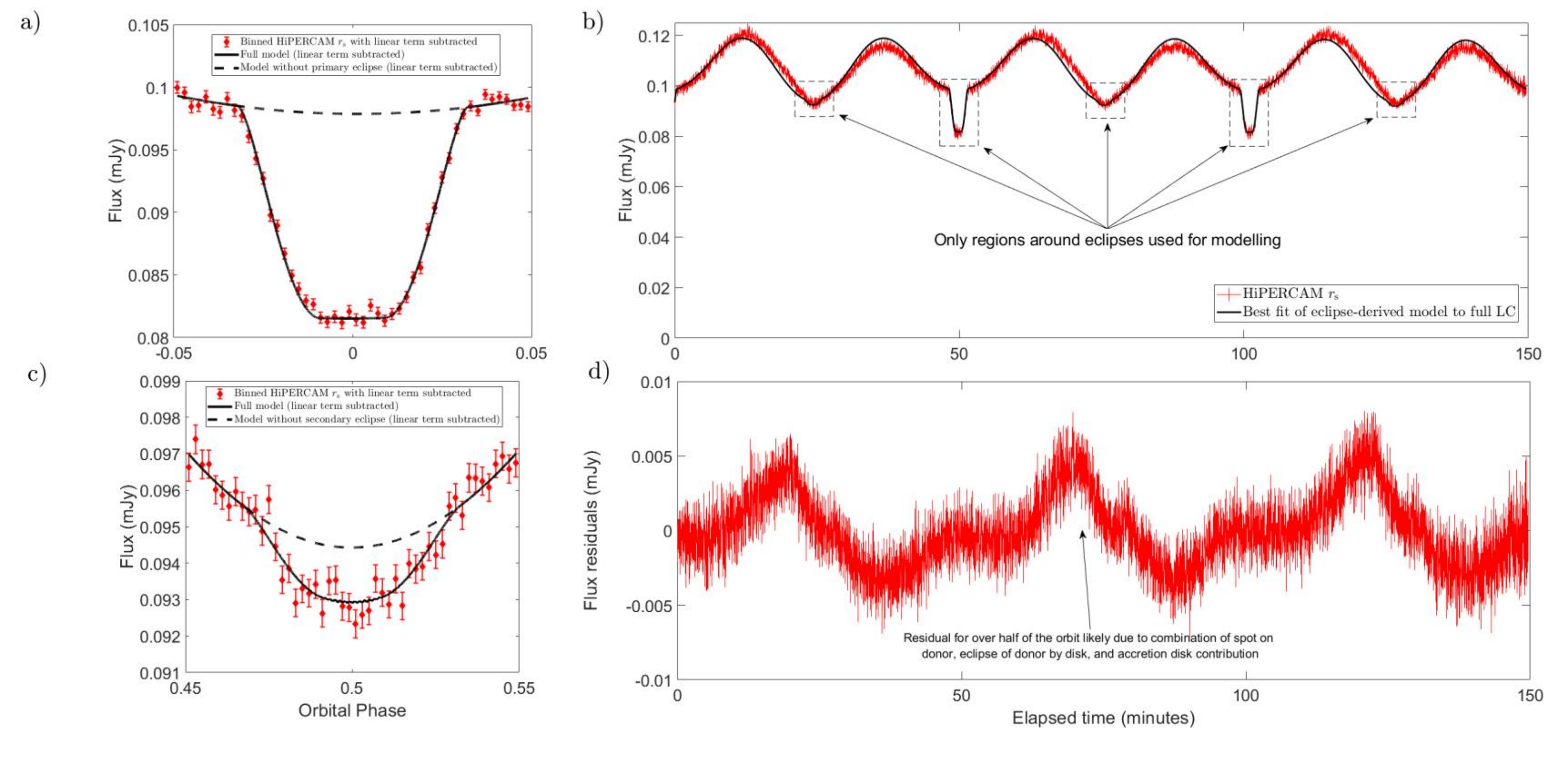
Some sneak peaks of new results:

- 62 min black widow candidate



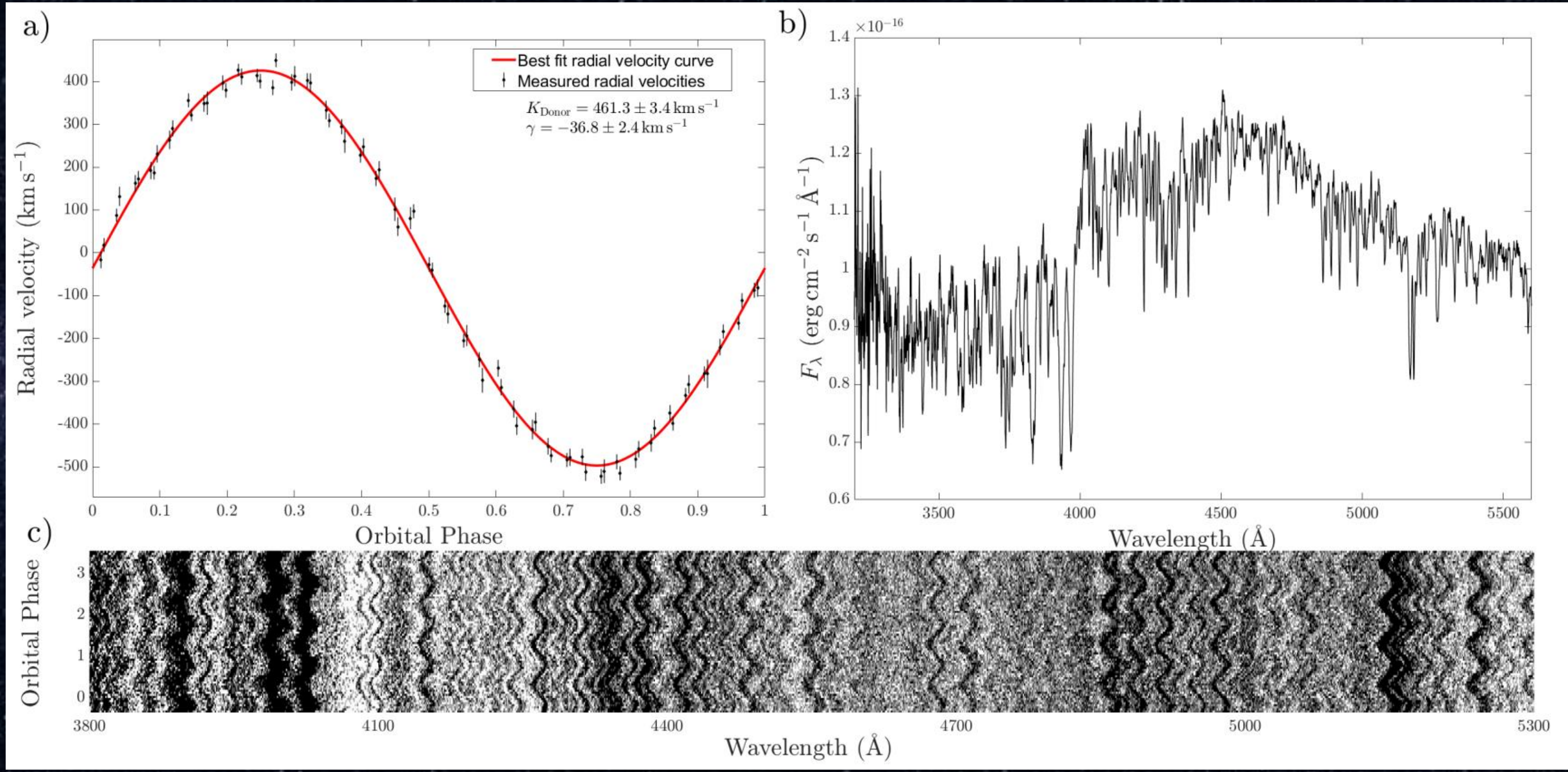
Some sneak peaks of new results:

- 51 min period



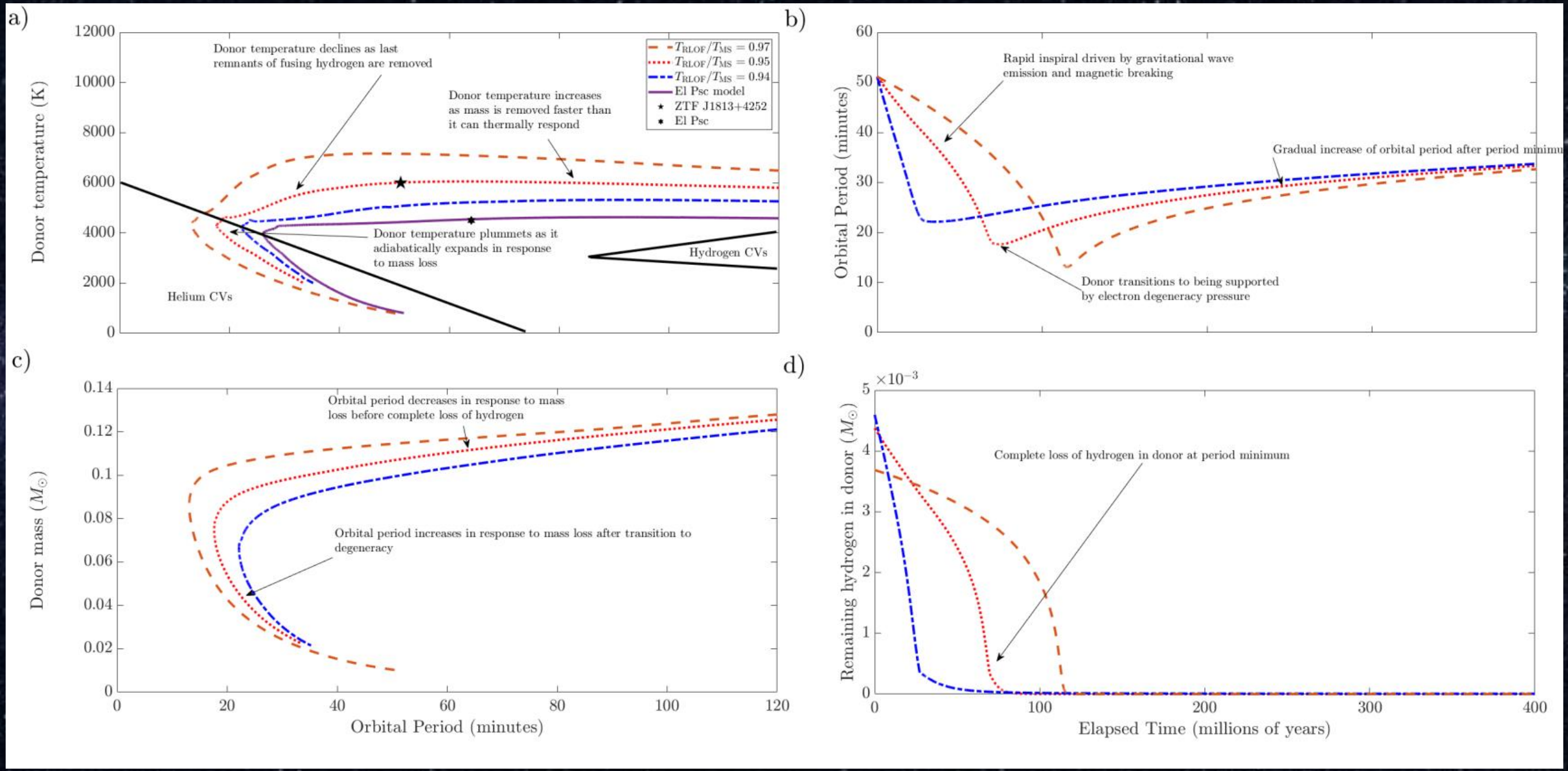
Some sneak peaks of new results:

- 51 min period
- F type spectrum!



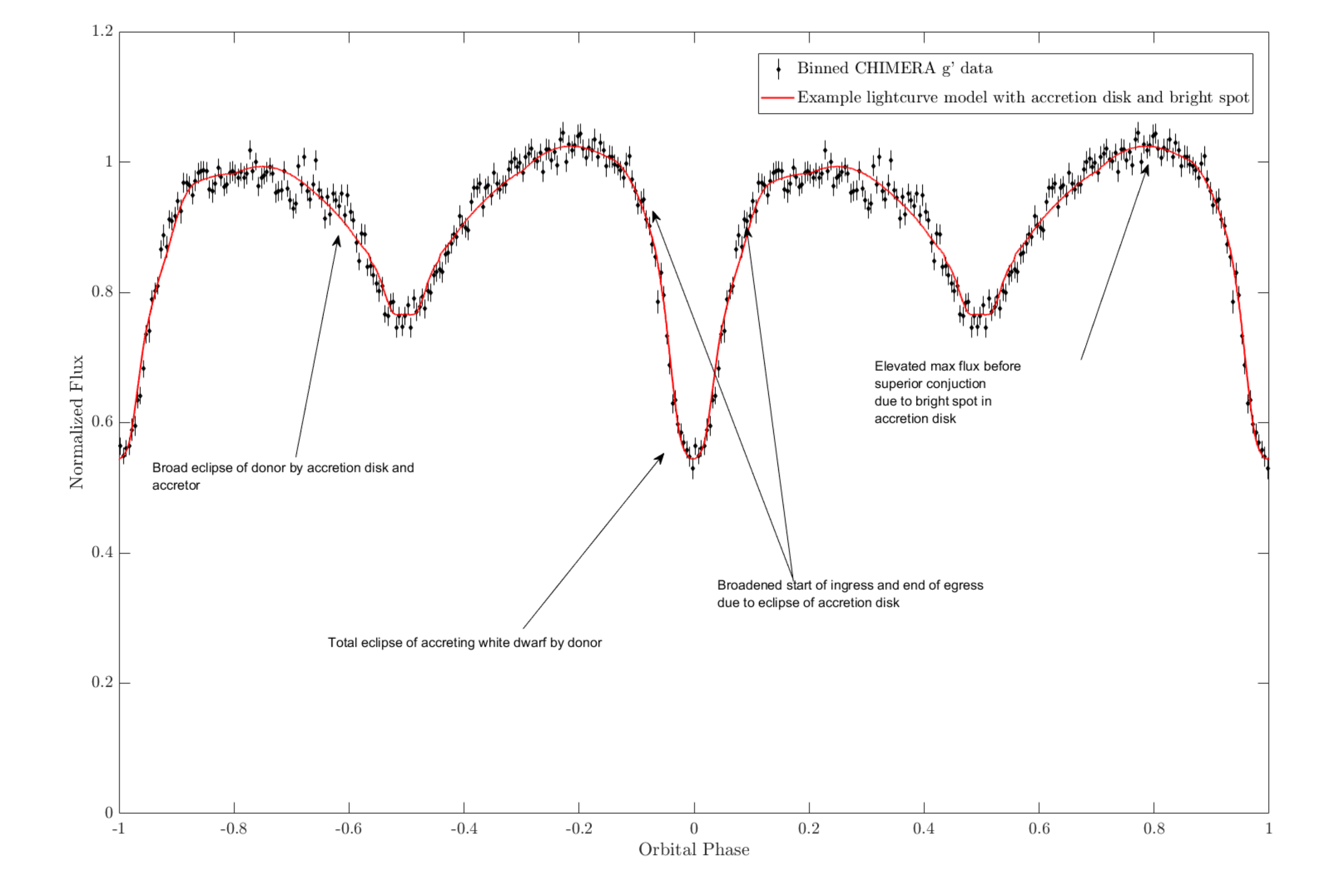
Some sneak peaks of new results:

- 51 min period
- F type spectrum!
- This will eventually evolve into the LISA band (long after LISA is gone)



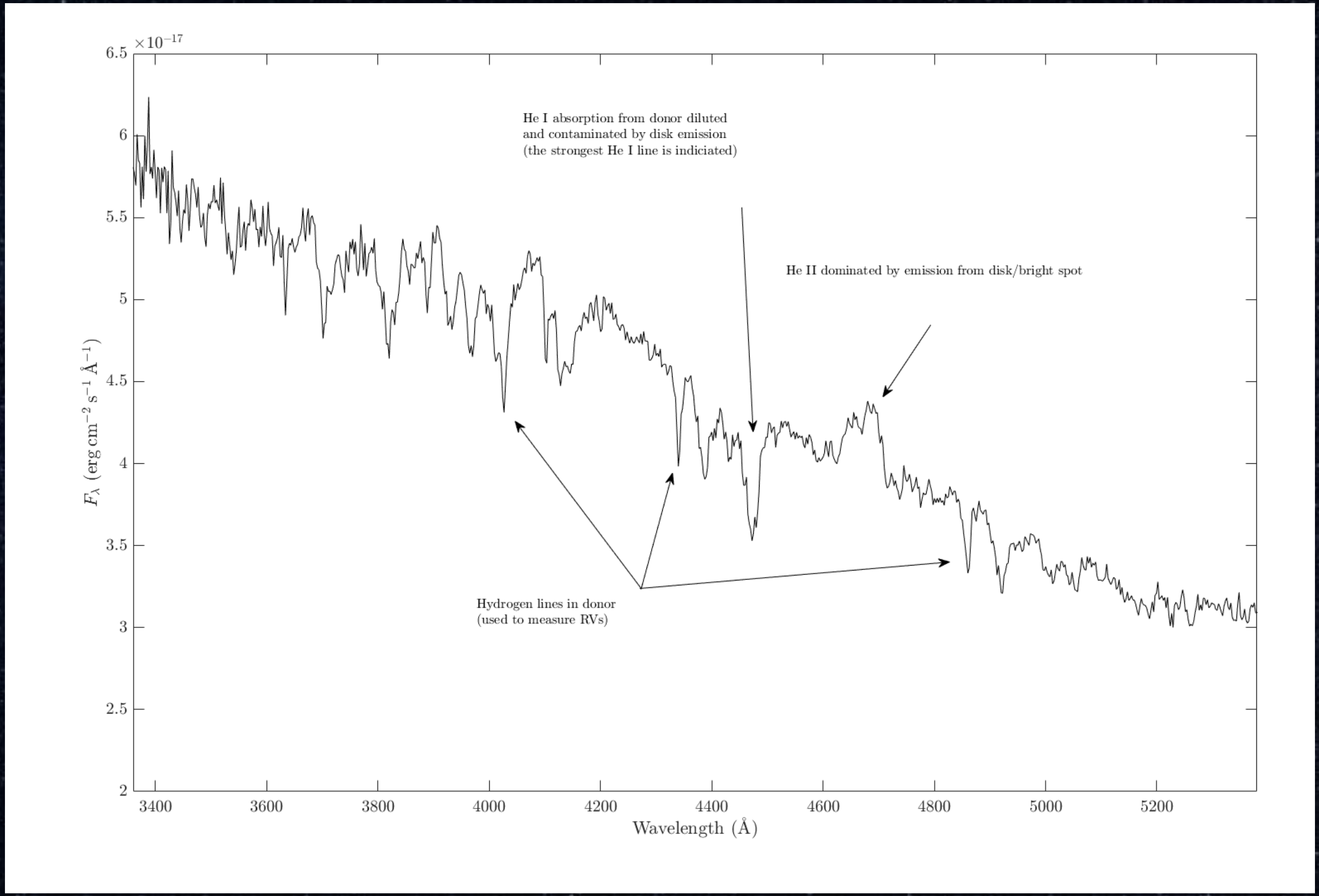
Some sneak peaks of new results:

- 13.7 min period



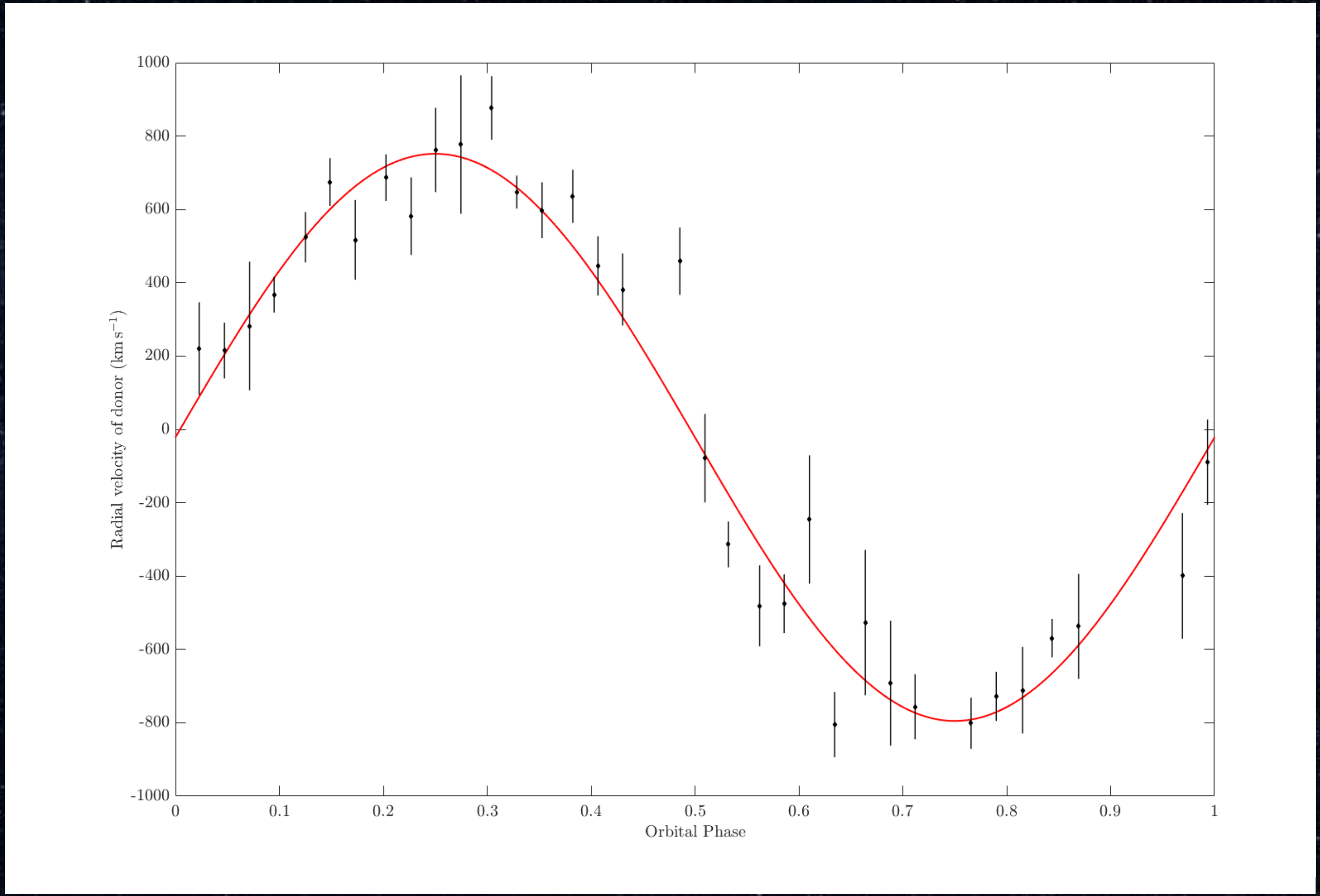
Some sneak peaks of new results:

- 13.7 min period
- You can see the donor!



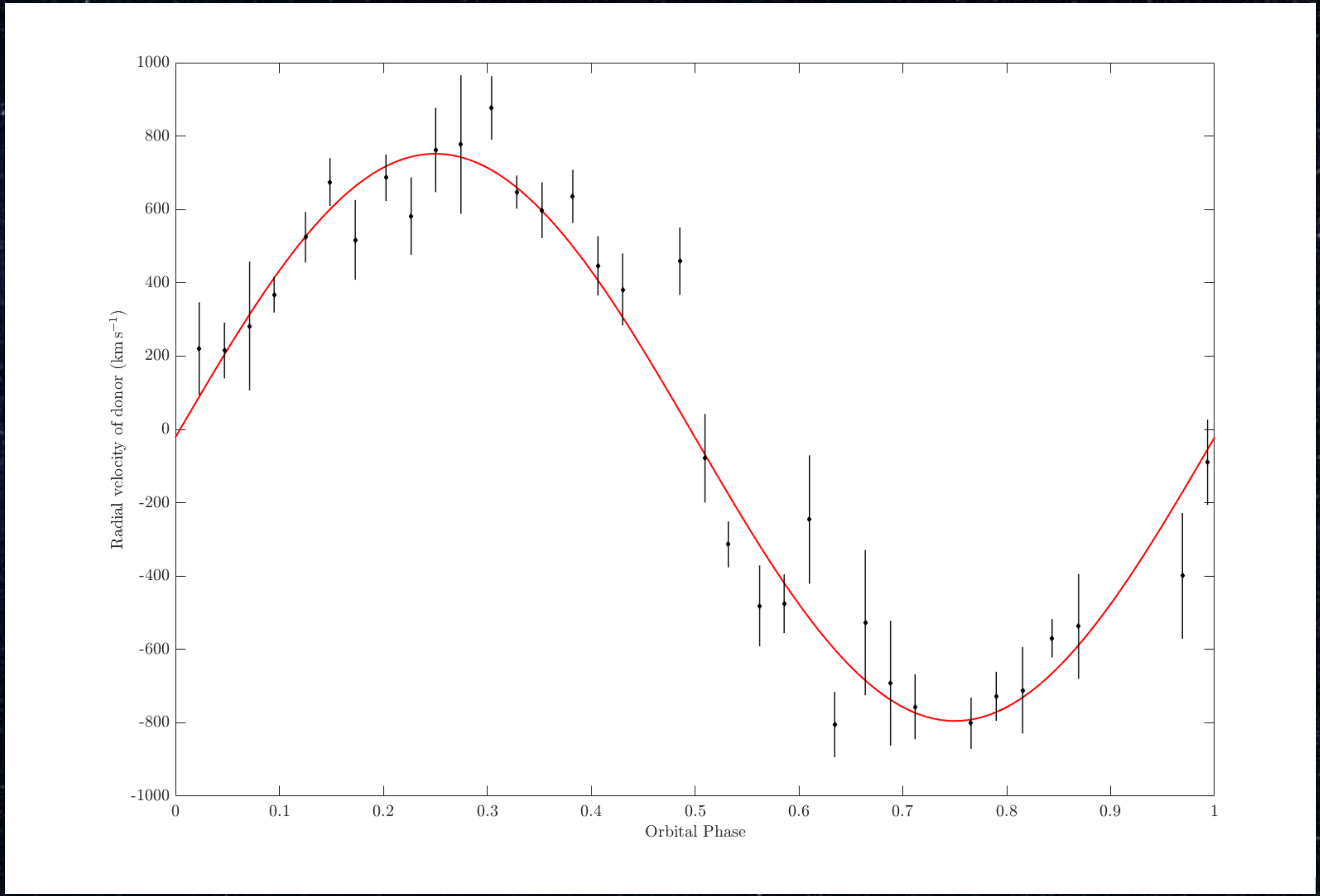
Some sneak peaks of new results:

- 13.7 min period
- You can see the donor!
- And it is really moving!



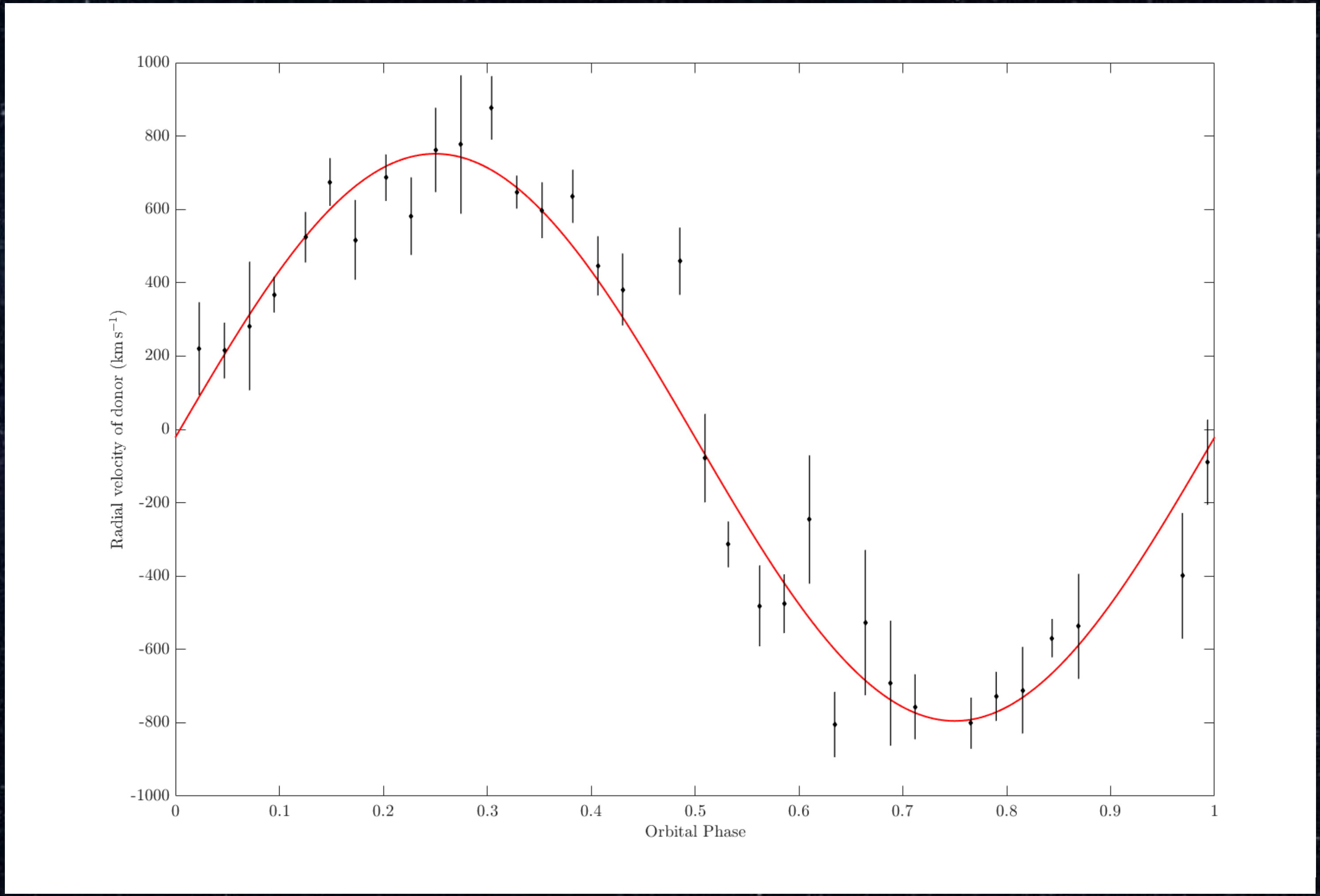
Some sneak peaks of new results:

- 13.7 min period
- You can see the donor!
- And it is really moving!
- And is LISA detectable (SNR~20)



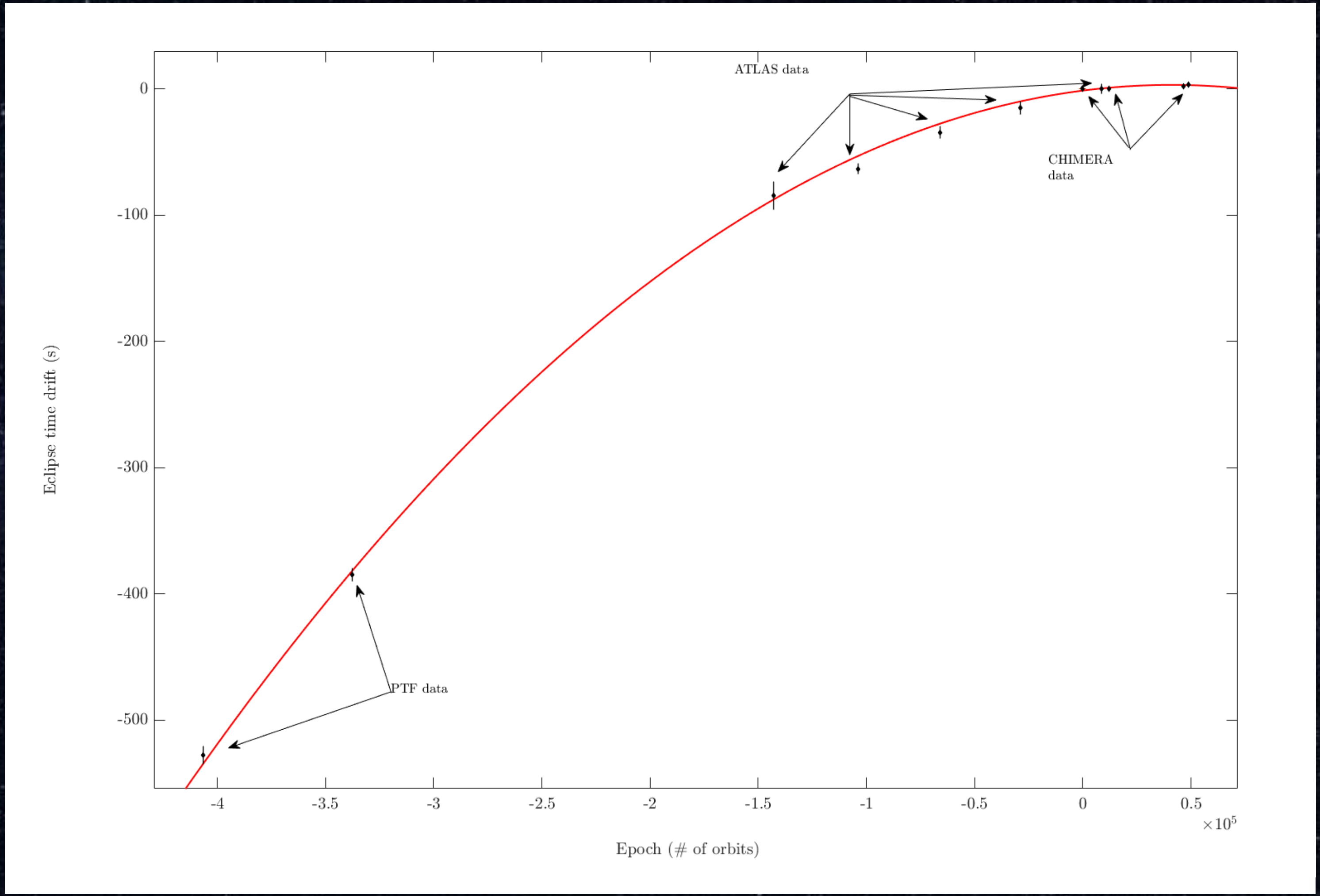
Some sneak peaks of new results:

- 13.7 min period
- You can see the donor!
- And it is really moving!
- And is LISA detectable (SNR~20)
- Has an x-ray counterpart!



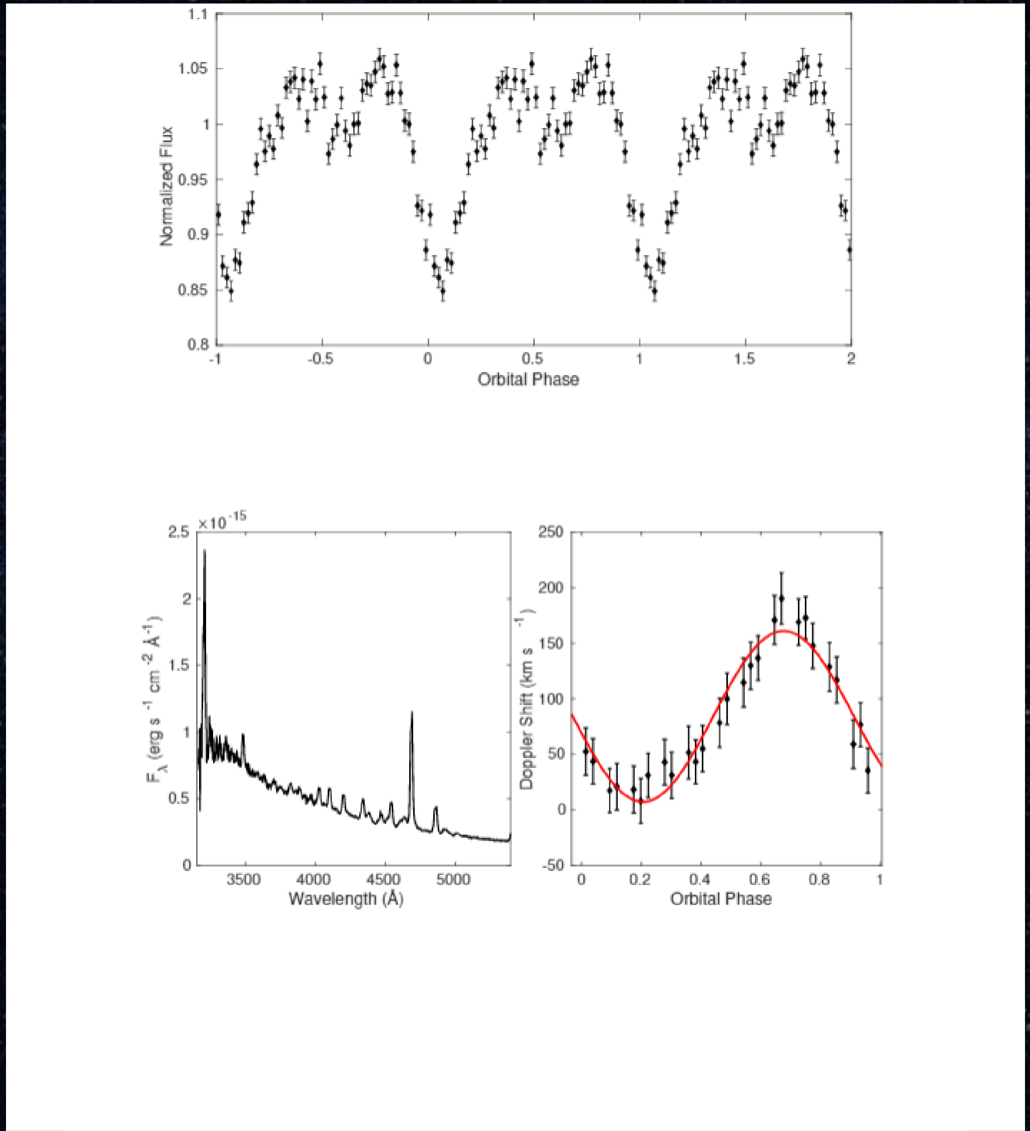
Some sneak peaks of new results:

- 13.7 min period
- You can see the donor!
- And it is really moving!
- And is LISA detectable (SNR~20)
- Has an x-ray counterpart!
- And orbital decay!



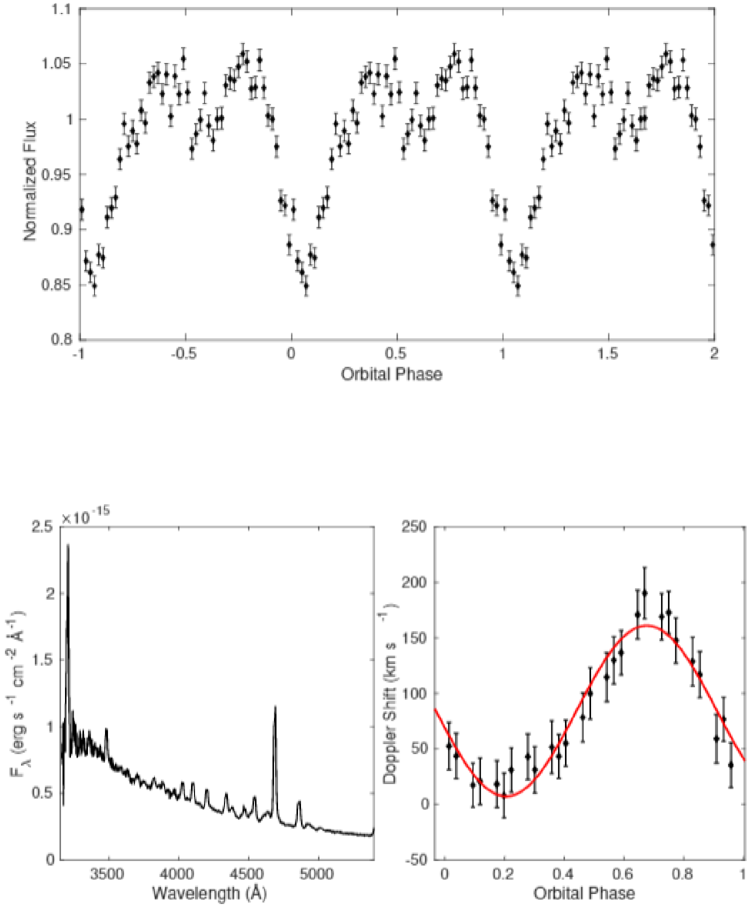
Some sneak peaks of new results:

- 7.9 min period AM CVn



Some sneak peaks of new results:

- 7.9 min period AM CVn
- Also comfortably in the LISA band



Looking to the future

- Many new wide field time domain surveys to explore, including TESS, LSST, Roman, etc. This field is going to undergo a revolution over the next decade from photon based discoveries.

- We will also see an expansion in powerful surveys at non-optical wavelengths, including AXIS, Roman. We should not underestimate how valuable these will be.

- Electromagnetic counterparts are what make most galactic LISA sources interesting. There may be a few that are interesting based on GWs alone, but the reality is that the information content of EM counterparts is incredibly rich compared to what can be encoded in gravitational waves.

What time-domain/multi-wavelength observations are critical for

answering fundamental science questions for this source?

>High angular resolution and deep surveys of the full Milky Way Galaxy, acquiring at least 500 epochs. Coverage at many wavelengths critical (x-ray, UV, optical, IR, radio).

Is this source a potential multi-messenger candidate (i.e., expected to be

detected in GW and/or particles/neutrinos)? If so, what is the

expected multimessenger output and the prospects for detection in the next

10 years?

>Yes, when LISA launches, these sources will represent the vast majority of all known multi-messenger sources in the field of astronomy. The work presented here demonstrates that the prospects for discovering them in the next 10 years using photons are incredibly bright. This is going to be the next big hot topic in astronomy.

What is needed for the time domain/multi-wavelength and/or multimessenger detections described above (more theory work, more

observations, new technology, new missions/facilities, etc.)?

>New missions/facilities and observations! We need an x-ray, IR, and UV time domain survey of the sky, especially the Galactic plane. We should focus on sampling optimized for detecting millihertz frequency flux variations in sources. As mentioned above, angular resolution is critical. We also need follow up facilities (for high time resolution spectroscopy and imaging).